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Leipold et al.

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(54) **TUNABLE RF FILTER PATHS FOR TUNABLE RF FILTER STRUCTURES**

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(73) Assignee: **Qorvo US, Inc.**, Greensboro, NC (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 82 days.

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Related U.S. Application Data

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(51) **Int. Cl.**
H03H 7/09   (2006.01)
H03H 7/42   (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC *H03H 7/0115* (2013.01); *H03F 1/565* (2013.01); *H03F 3/193* (2013.01); *H03F 3/245* (2013.01);
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(58) **Field of Classification Search**
CPC H03H 2001/0085; H03H 7/0115; H03H 7/09; H03H 7/1775; H03H 7/0153

USPC 333/174, 175, 185
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,597,709 A	8/1971	Rhodes	
3,718,874 A *	2/1973	Cooper, Jr.	H03H 7/0161
			333/204

(Continued)

FOREIGN PATENT DOCUMENTS

EP	1184977 A2	3/2002
JP	07015253 A	1/1995

(Continued)

OTHER PUBLICATIONS

Non-Final Office Action for U.S. Appl. No. 14/298,829, mailed Jun. 22, 2015, 8 pages.

(Continued)

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Assistant Examiner — Rakesh Patel
(74) *Attorney, Agent, or Firm* — Withrow & Terranova, P.L.L.C.

(57) **ABSTRACT**

This disclosure relates generally to radio frequency (RF) filter structures. In one embodiment, an RF filter structure includes a first resonator and a second resonator. The second resonator is operably associated with the first resonator such that an energy transfer factor between the first resonator and the second resonator is less than 10%. The first resonator includes a first inductor and a first capacitive structure electrically connected to the first inductor, while the second resonator has a second inductor and a second capacitive structure electrically connected to the second inductor. A displacement between the first inductor and the second inductor is less than or equal to half a maximum lateral width of the second inductor. To set an electric coupling coefficient, a first cross-coupling capacitive structure is electrically connected between the first resonator and the second resonator.
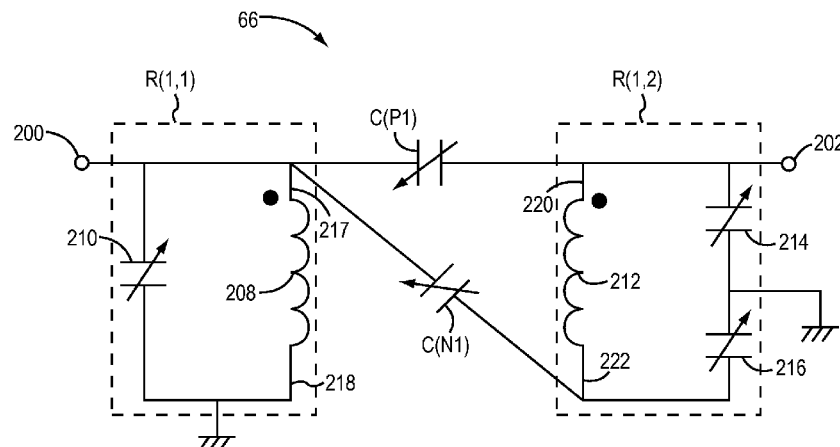
27 Claims, 37 Drawing Sheets

Related U.S. Application Data

application No. 61/949,581, filed on Mar. 7, 2014, provisional application No. 61/951,844, filed on Mar. 12, 2014, provisional application No. 61/982,946, filed on Apr. 23, 2014, provisional application No. 61/982,952, filed on Apr. 23, 2014, provisional application No. 61/982,971, filed on Apr. 23, 2014, provisional application No. 61/938,884, filed on Feb. 12, 2014, provisional application No. 62/008,192, filed on Jun. 5, 2014.

(51) **Int. Cl.**

H03H 7/46	(2006.01)
H03H 7/01	(2006.01)
H03F 3/193	(2006.01)
H04B 1/10	(2006.01)
H03F 1/56	(2006.01)
H03F 3/24	(2006.01)
H03F 3/68	(2006.01)
H03F 3/72	(2006.01)
H04B 1/18	(2006.01)

(52) **U.S. Cl.**
CPC .. *H03F 3/68* (2013.01); *H03F 3/72* (2013.01); *H03H 7/09* (2013.01); *H03H 7/1775* (2013.01); *H04B 1/1027* (2013.01); *H04B 1/18* (2013.01); *H03F 2200/111* (2013.01); *H03F 2200/267* (2013.01); *H03F 2200/451* (2013.01); *H03F 2203/7209* (2013.01); *H03H 2210/012* (2013.01); *H03H 2210/025* (2013.01); *H03H 2210/04* (2013.01)

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,794,941	A	2/1974	Templin
4,361,894	A	11/1982	Kurihara et al.
5,661,414	A	8/1997	Shigehara et al.
5,689,144	A	11/1997	Williams
5,841,330	A	11/1998	Wenzel et al.
5,880,620	A	3/1999	Gitlin et al.
5,896,073	A	4/1999	Miyazaki et al.
5,963,557	A	10/1999	Eng
6,233,438	B1	5/2001	Wynn
6,529,750	B1	3/2003	Zhang et al.
6,664,873	B2	12/2003	Tiihonen
6,801,102	B2	10/2004	Shamsaifar et al.
7,015,870	B2	3/2006	Guitton et al.
7,116,186	B2	10/2006	Chen
7,795,995	B2	9/2010	White et al.
7,825,751	B2	11/2010	Kawaguchi et al.
8,204,446	B2	6/2012	Scheer et al.
8,314,653	B1	11/2012	Granger-Jones et al.
8,626,083	B2	1/2014	Greene et al.
8,736,511	B2	5/2014	Morris, III
8,742,871	B2	6/2014	Jin et al.
8,751,993	B1	6/2014	Fenzi et al.
8,791,769	B2	7/2014	Leong et al.
8,803,632	B2	8/2014	Takeuchi
8,803,634	B2	8/2014	Hanaoka
8,841,983	B2	9/2014	Newton et al.
8,884,714	B2	11/2014	Carey et al.
8,977,216	B2	3/2015	Weissman et al.
9,002,309	B2	4/2015	Sahota et al.
9,054,648	B1	6/2015	Xu
9,094,104	B2	7/2015	Din et al.
9,124,355	B2	9/2015	Black et al.
9,203,455	B2	12/2015	Yang et al.
2001/0020877	A1	9/2001	Hasegawa et al.
2002/0057139	A1	5/2002	Matsumura et al.
2003/0008577	A1	1/2003	Quigley et al.
2003/0151409	A1	8/2003	Marek
2003/0222732	A1	12/2003	Matthaei
2004/0127178	A1	7/2004	Kuffner
2004/0130414	A1	7/2004	Marquardt et al.
2004/0162042	A1	8/2004	Chen et al.
2004/0196085	A1	10/2004	Shen
2004/0222868	A1	11/2004	Rathgeber et al.
2004/0266378	A1	12/2004	Fukamachi et al.
2005/0195063	A1	9/2005	Mattsson
2005/0237144	A1	10/2005	Einsinger et al.
2006/0033602	A1	2/2006	Mattsson
2006/0035600	A1	2/2006	Lee et al.
2006/0038635	A1*	2/2006	Richiuso H01F 17/0006 333/177
2006/0125465	A1	6/2006	Xiang et al.
2006/0220727	A1	10/2006	Yen
2006/0226943	A1	10/2006	Marques
2006/0261890	A1	11/2006	Floyd et al.
2006/0281431	A1	12/2006	Isaac et al.
2007/0091006	A1	4/2007	Thober et al.
2007/0161361	A1	7/2007	Vaisanen et al.
2007/0182520	A1	8/2007	Kawakubo et al.
2007/0194859	A1	8/2007	Brobston et al.
2007/0241839	A1*	10/2007	Taniguchi H03H 7/09 333/185
2008/0122560	A1	5/2008	Liu
2008/0220735	A1	9/2008	Kim et al.
2008/0297299	A1	12/2008	Yun et al.
2010/0188171	A1*	7/2010	Mohajer-Iravani ... H01P 1/2005 333/175
2010/0283557	A1*	11/2010	Taniguchi H01P 1/20345 333/204
2011/0010749	A1	1/2011	Alkan
2011/0103494	A1	5/2011	Ahmadi
2011/0156835	A1	6/2011	Nagai
2011/0163824	A1	7/2011	Kawano
2011/0169589	A1	7/2011	Franzon et al.
2011/0210787	A1	9/2011	Lee et al.
2011/0241163	A1	10/2011	Liu et al.
2012/0051409	A1	3/2012	Brobston et al.
2012/0081192	A1	4/2012	Hanaoka
2012/0230227	A1	9/2012	Weiss
2012/0249266	A1	10/2012	Lim et al.
2012/0262252	A1	10/2012	Tseng et al.
2013/0049902	A1	2/2013	Hendry et al.
2013/0244591	A1	9/2013	Weissman et al.
2013/0295863	A1	11/2013	Shanan
2014/0035358	A1*	2/2014	Ichikawa H04B 5/0037 307/9.1
2014/0106698	A1	4/2014	Mi et al.
2014/0133189	A1	5/2014	Worek
2014/0146737	A1	5/2014	Ohshima et al.
2014/0162712	A1	6/2014	Feld et al.
2014/0167877	A1	6/2014	Shimizu et al.
2014/0192845	A1	7/2014	Szini et al.
2014/0225680	A1	8/2014	Fujiwara et al.
2014/0232467	A1	8/2014	Mukai et al.
2014/0285286	A1	9/2014	Bojer
2014/0323071	A1	10/2014	Liao
2014/0328220	A1	11/2014	Khlat et al.
2015/0002240	A1	1/2015	Reiha
2015/0116950	A1	4/2015	Yoo et al.

FOREIGN PATENT DOCUMENTS

JP	2010141827 A	6/2010
KR	100812098 B1	3/2008
WO	0146971 A1	6/2001
WO	2005117255 A1	12/2005

OTHER PUBLICATIONS

Hoppenjans, Eric E. et al., "A Vertically Integrated Tunable UHF Filter," International Microwave Symposium Digest (MTT), May 23-28, 2010, Anaheim, California, IEEE, pp. 1380-1383.

Joshi, H. et al., "Tunable high Q narrow-band triplexer," IEEE MTT-S International Microwave Symposium Digest, Jun. 7-12, 2009, Boston, MA, IEEE, pp. 1477-1480.

Kamali-Sarvestani, Reza et al., "Fabrication of High Quality Factor RF-Resonator Using Embedded Inductor and Via Capacitor,"

(56)　　　　　　**References Cited**

OTHER PUBLICATIONS

IECON 2010—36th Annual Conference on IEEE Industrial Electronics Society, Nov. 7-10, 2010, Glendale, Arizona, IEEE, pp. 2283-2287.

International Search Report and Written Opinion for PCT/US2014/030431, mailed Jun. 20, 2014, 14 pages.

Invitation to Pay Additional Fees and, Where Applicable, Protest Fee for PCT/US2014/048608, mailed Oct. 21, 2014, 7 pages.

International Search Report and Written Opinion for PCT/US2014/048608, mailed Dec. 16, 2014, 18 pages.

Non-Final Office Action for U.S. Appl. No. 14/555,053, mailed Dec. 31, 2015, 5 pages.

Non-Final Office Action for U.S. Appl. No. 14/298,863, mailed Jan. 7, 2016, 16 pages.

Non-Final Office Action for U.S. Appl. No. 14/298,852, mailed Dec. 22, 2015, 7 pages.

Non-Final Office Action for U.S. Appl. No. 14/450,028, mailed Dec. 10, 2015, 11 pages.

International Preliminary Report on Patentability for PCT/US/2014/030431, mailed Sep. 24, 2015, 10 pages.

Non-Final Office Action for U.S. Appl. No. 14/215,800, mailed Nov. 20, 2015, 5 pages.

Final Office Action for U.S. Appl. No. 14/215,800, mailed Mar. 11, 2016, 6 pages.

Final Office Action for U.S. Appl. No. 14/298,829, mailed Feb. 3, 2016, 10 pages.

Non-Final Office Action for U.S. Appl. No. 14/450,156, mailed Mar. 14, 2016, 11 pages.

Non-Final Office Action for U.S. Appl. No. 14/450,200, mailed Feb. 29, 2016, 13 pages.

International Preliminary Report on Patentability for PCT/US2014/048608, mailed Feb. 11, 2016, 14 pages.

Notice of Allowance for U.S. Appl. No. 14/298,829, mailed May 20, 2016, 9 pages.

Non-Final Office Action for U.S. Appl. No. 14/449,913, mailed Mar. 28, 2016, 15 pages.

Notice of Allowance for U.S. Appl. No. 14/298,852, mailed May 13, 2016, 9 pages.

Final Office Action for U.S. Appl. No. 14/450,028, mailed Mar. 31, 2016, 12 pages.

Non-Final Office Action for U.S. Appl. No. 14/449,764, mailed May 4, 2016, 12 pages.

Non-Final Office Action for U.S. Appl. No. 14/450,199, mailed Apr. 20, 2016, 7 pages.

Non-Final Office Action for U.S. Appl. No. 14/450,204, mailed Apr. 22, 2016, 8 pages.

Notice of Allowance for U.S. Appl. No. 14/555,053, mailed Apr. 19, 2016, 7 pages.

Final Office Action for U.S. Appl. No. 14/298,863, mailed Jun. 3, 2016, 17 pages.

Final Office Action for U.S. Appl. No. 14/450,200, mailed Jun. 14, 2016, 13 pages.

Non-Final Office Action for U.S. Appl. No. 14/555,557, mailed Jun. 13, 2016, 28 pages.

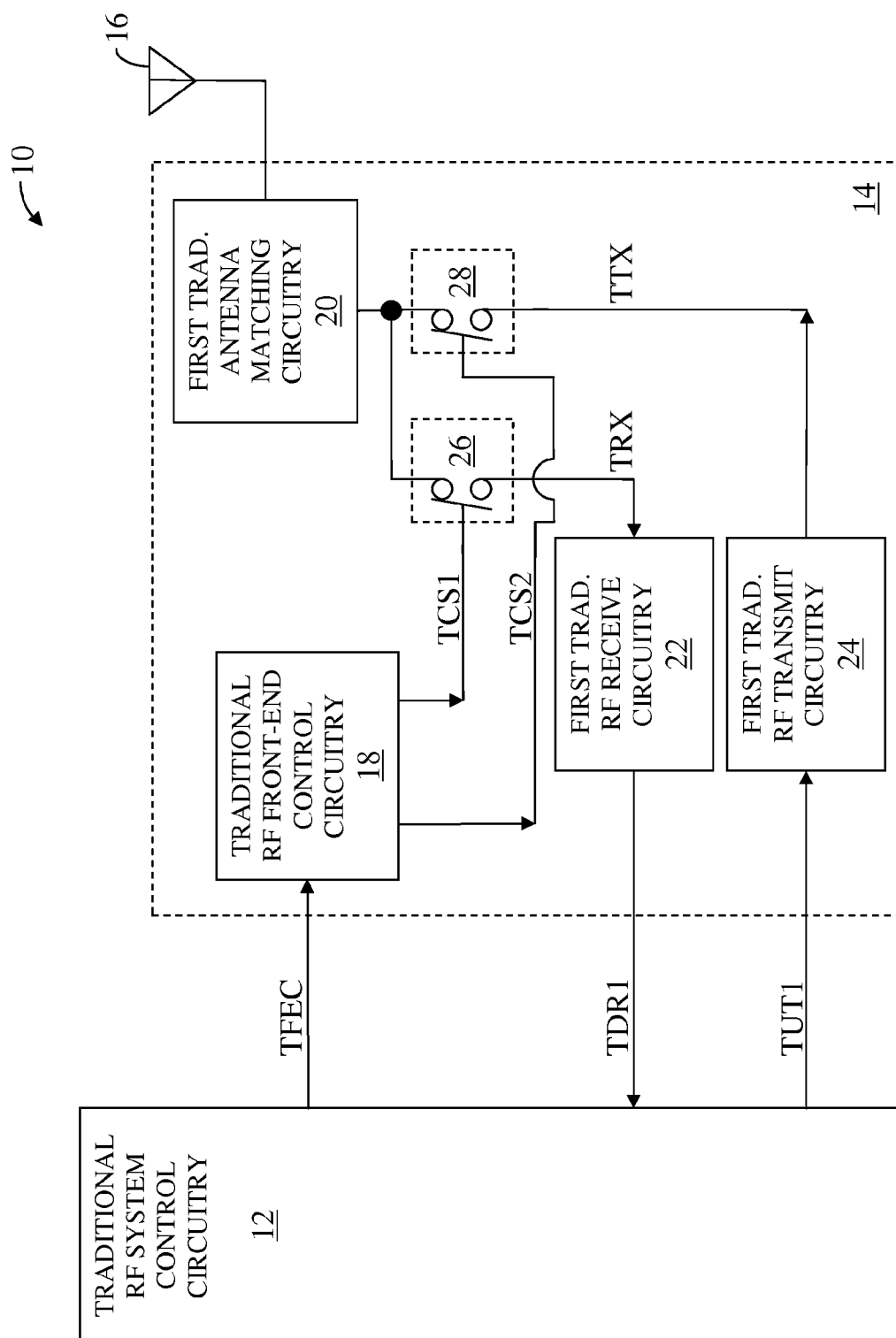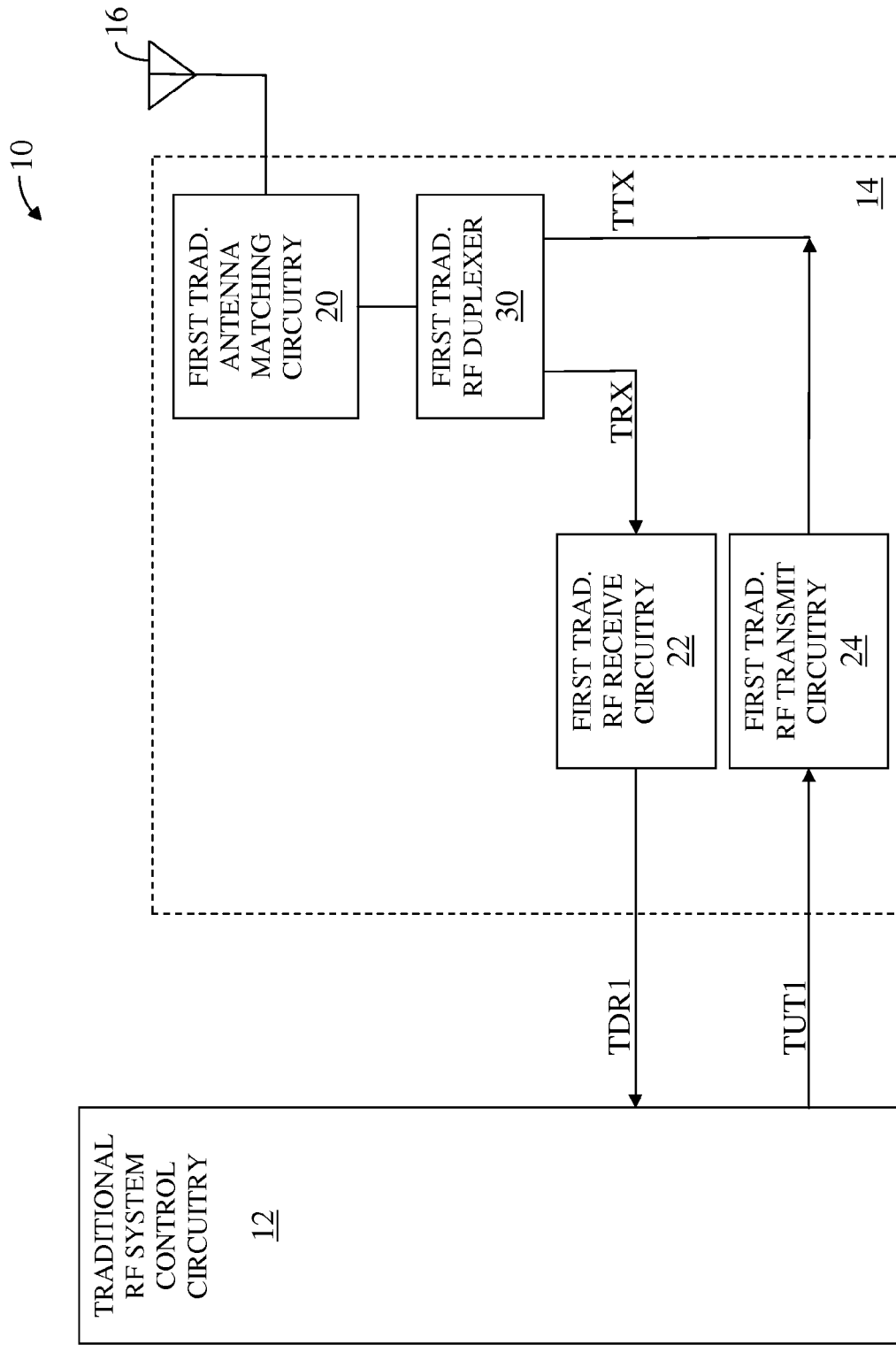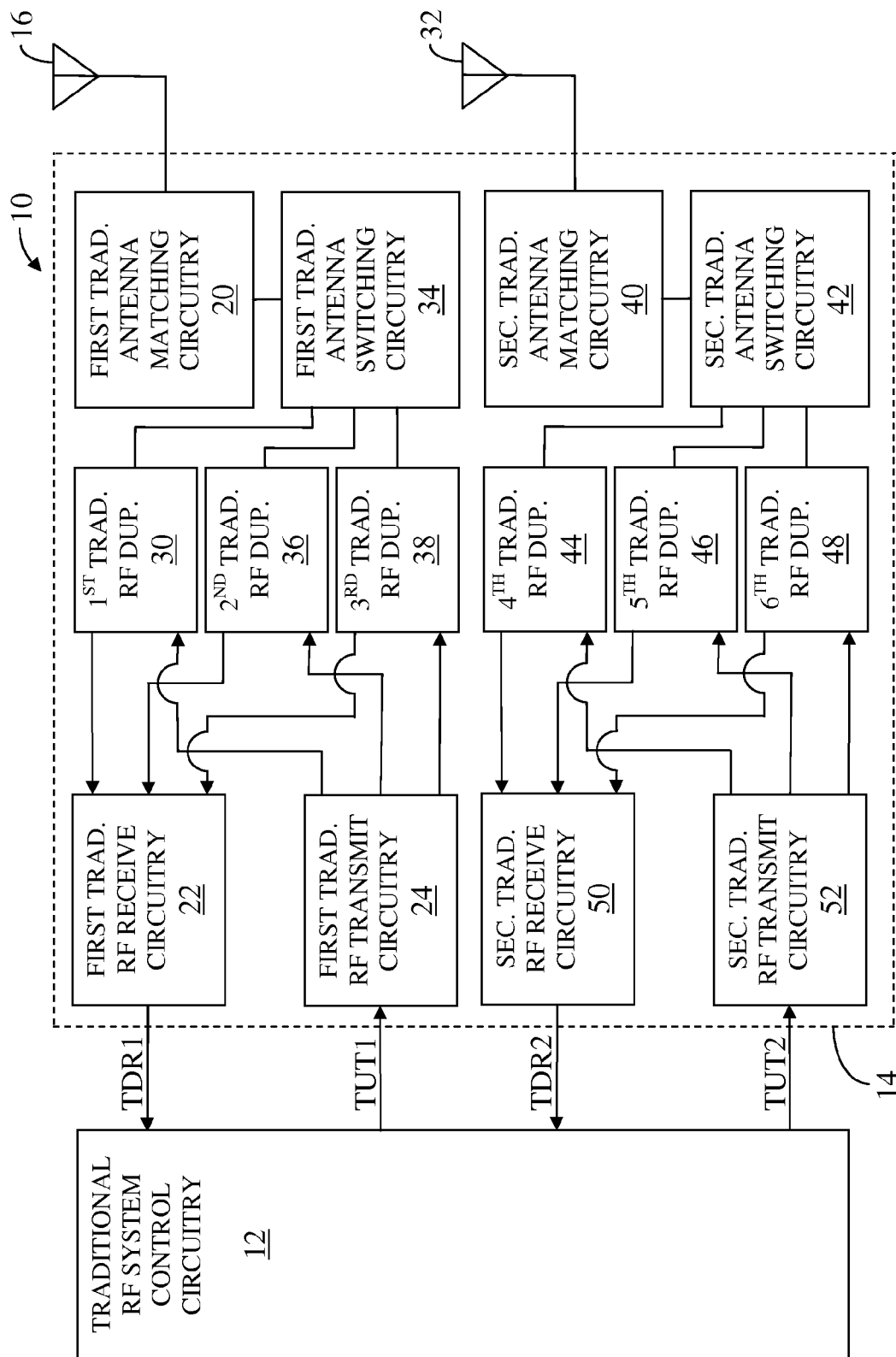Non-Final Office Action for U.S. Appl. No. 14/554,943, mailed Jun. 30, 2016, 14 pages.

* cited by examiner

FIG. 1 – Prior Art

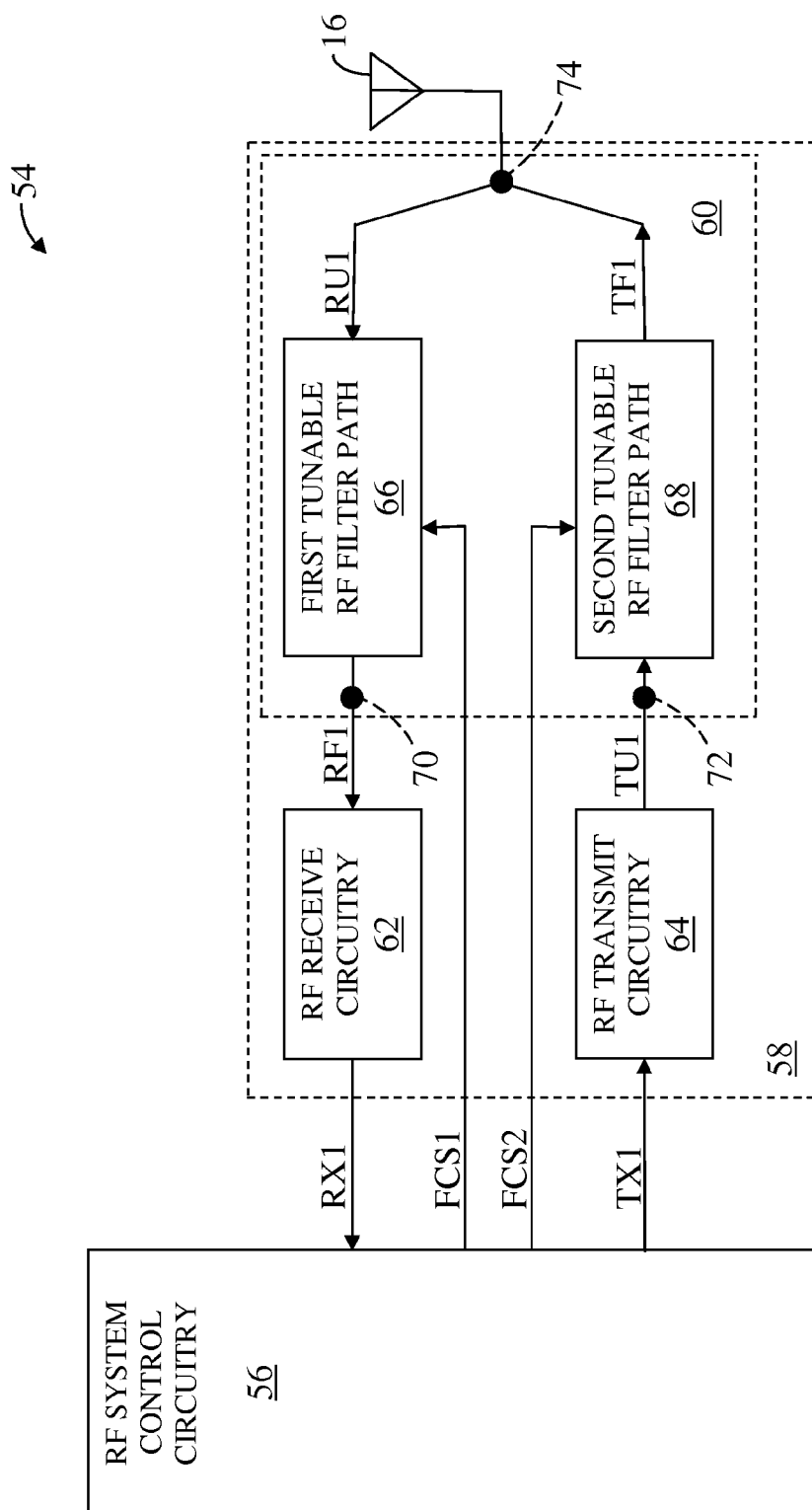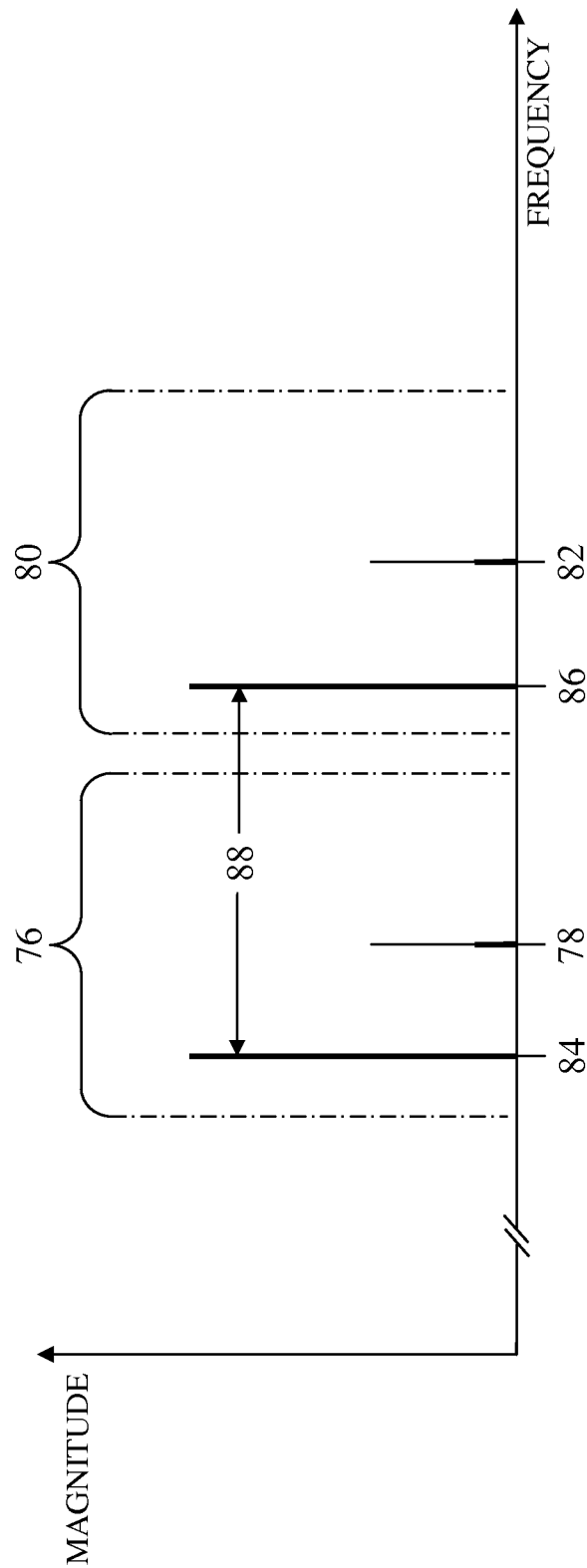FIG. 2 – Prior Art

FIG. 3 – Prior Art

FIG. 4

FIG. 5

FIG. 6A

FIG. 6B
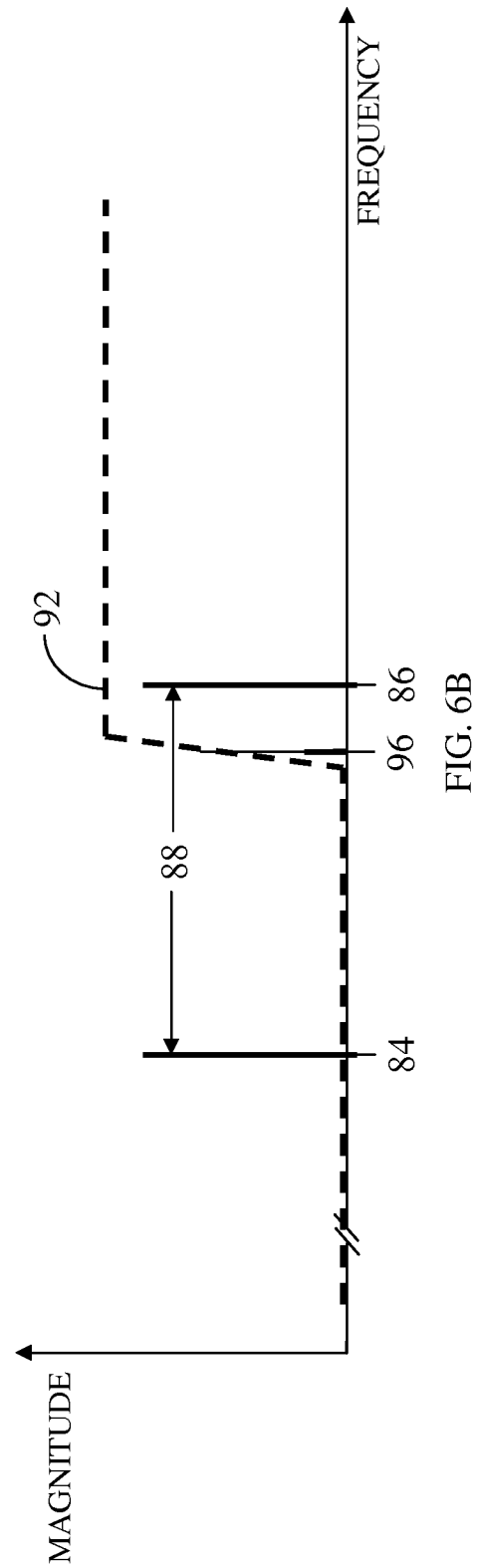
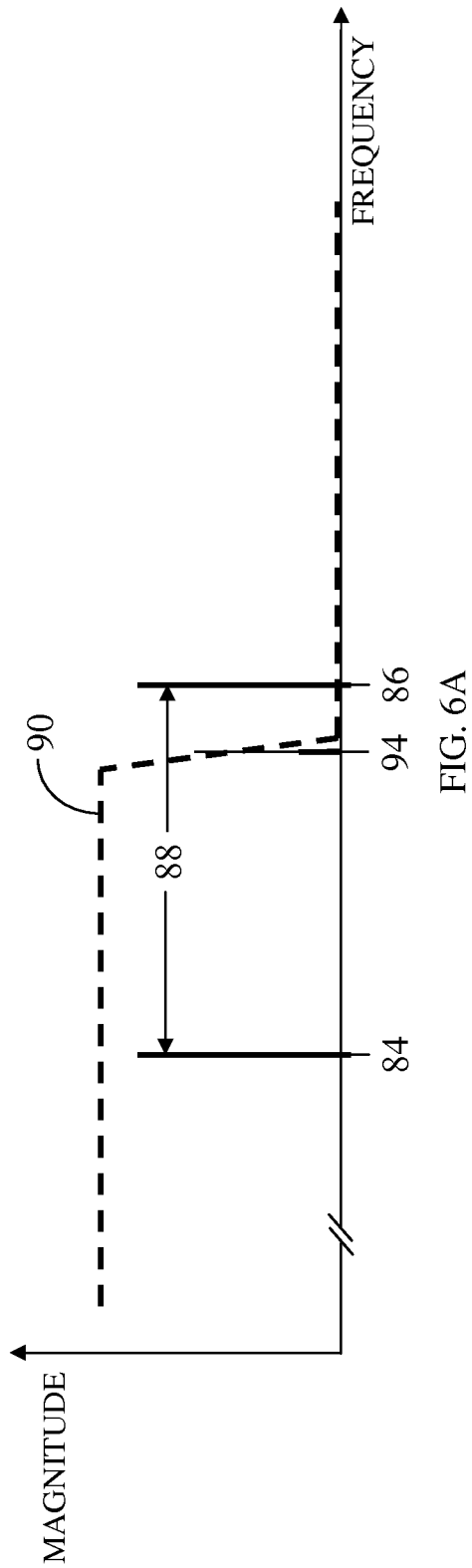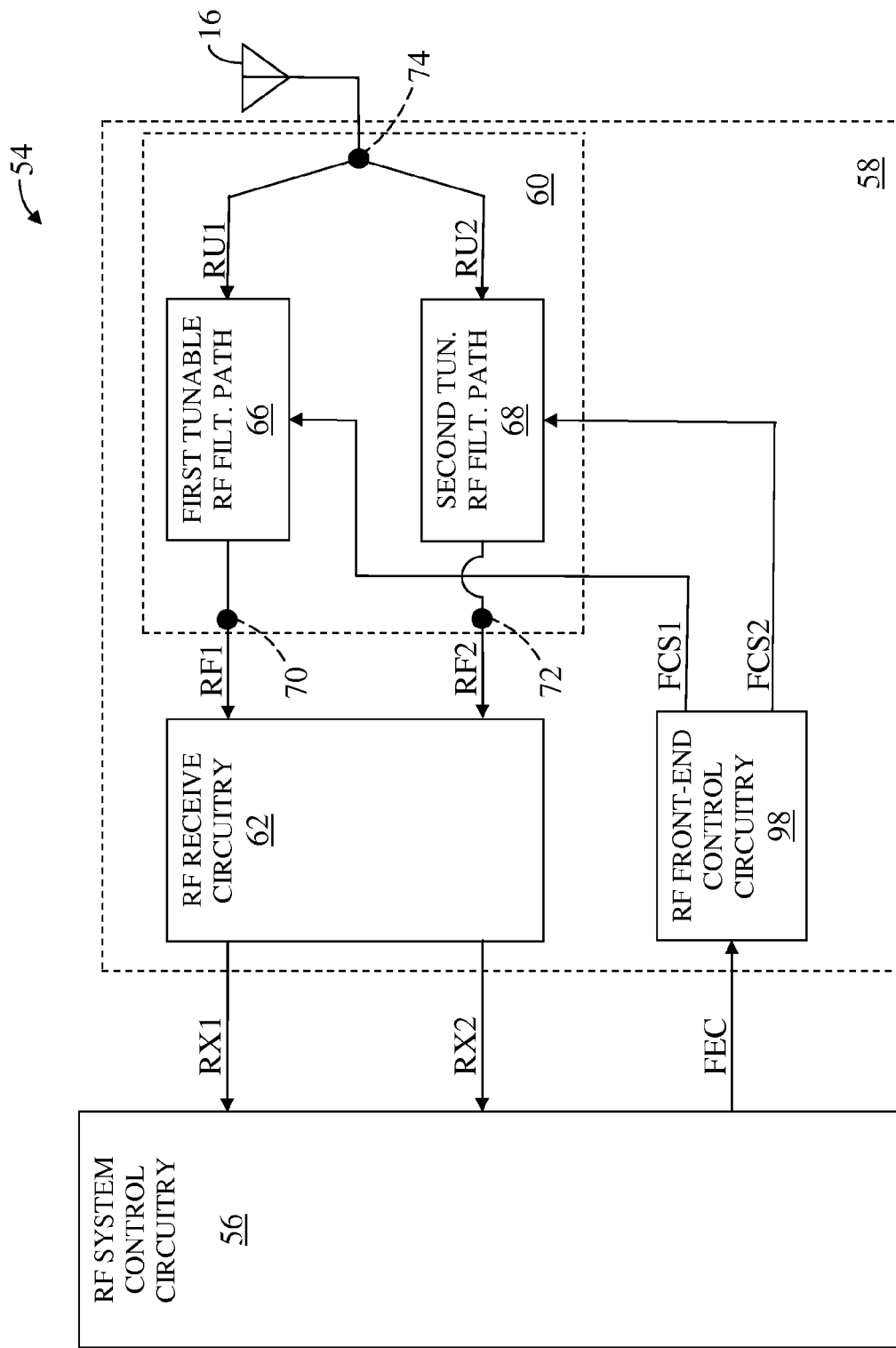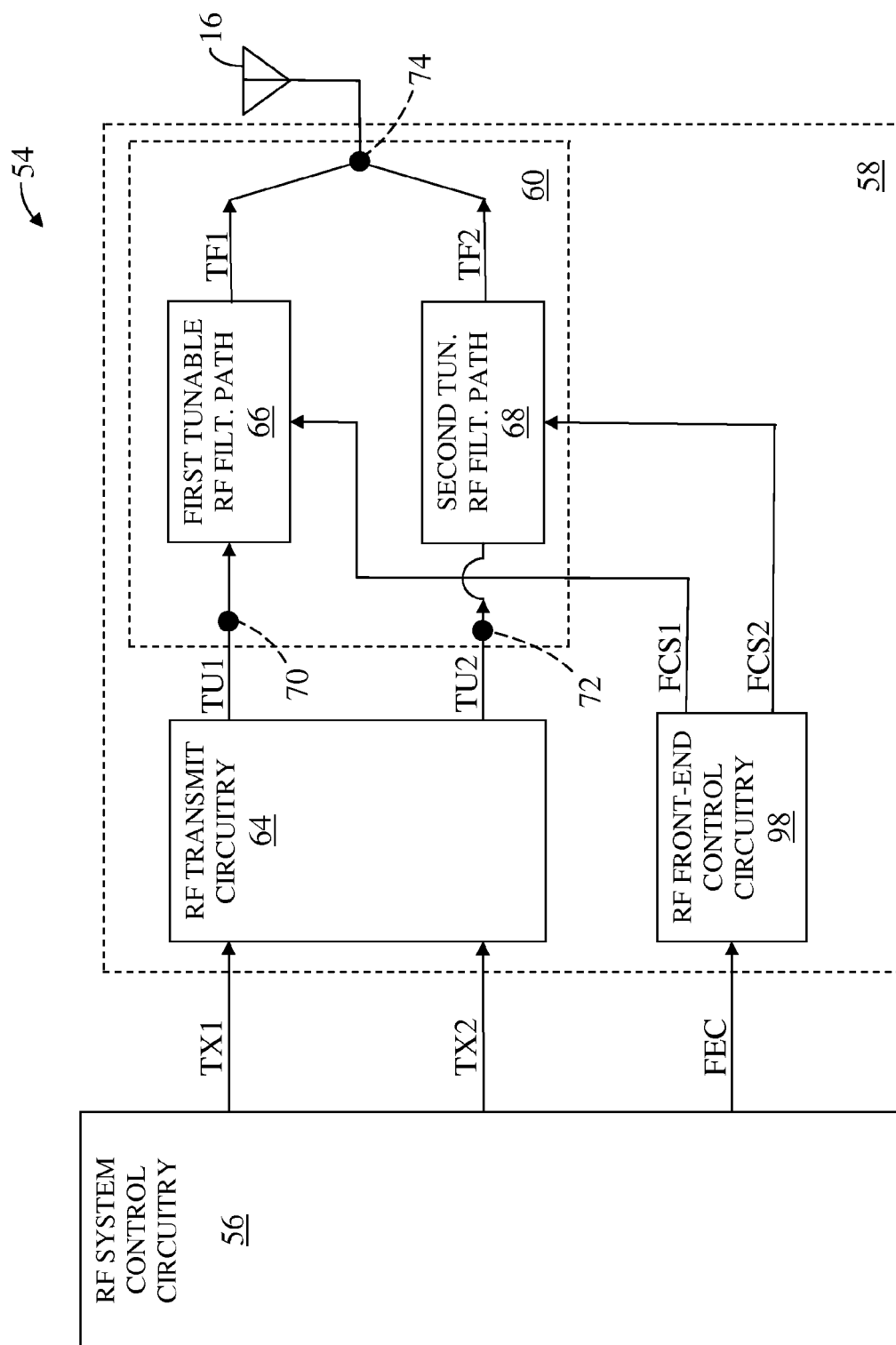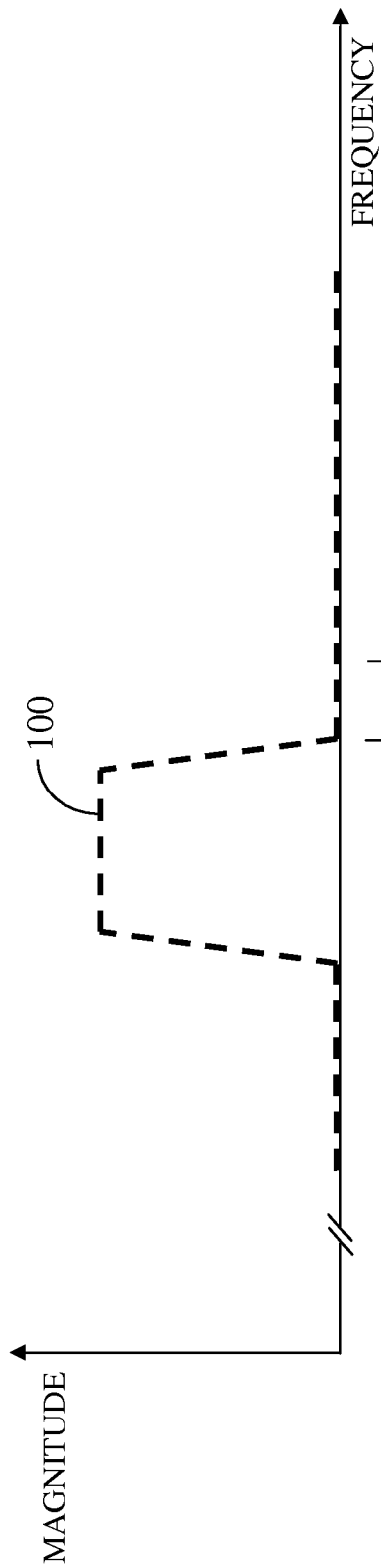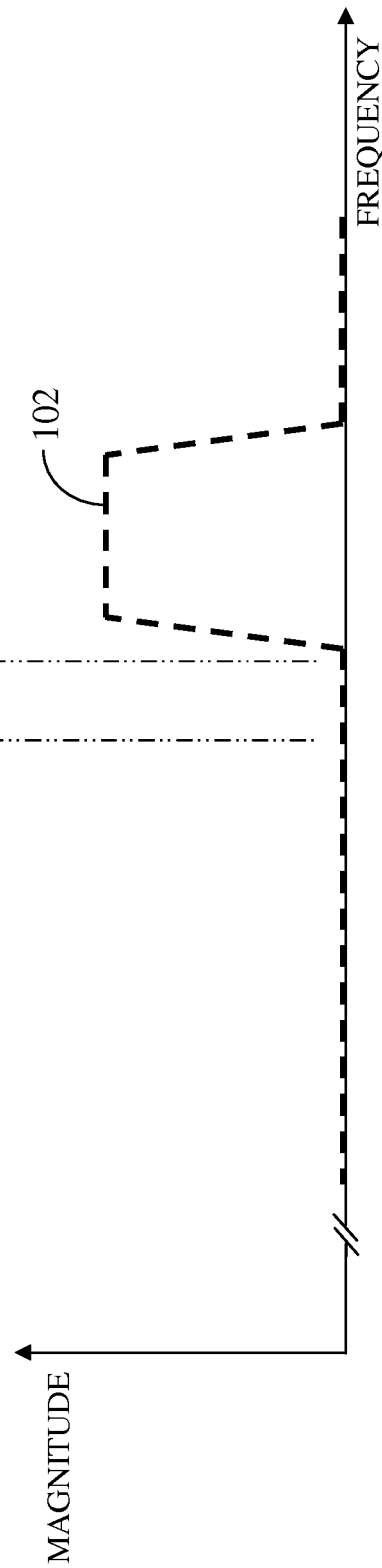FIG. 7

FIG. 8

FIG. 9A

FIG. 9B
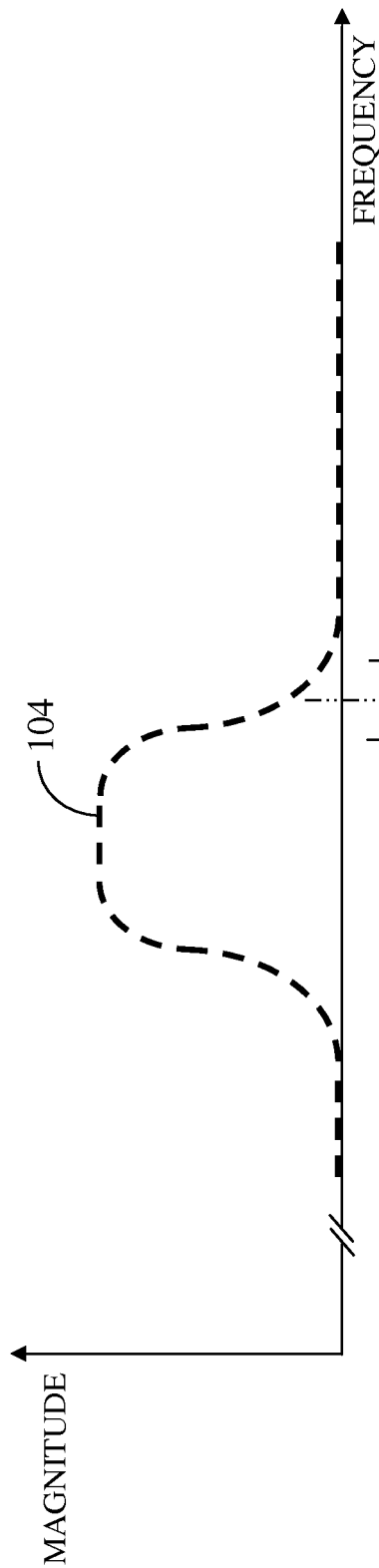
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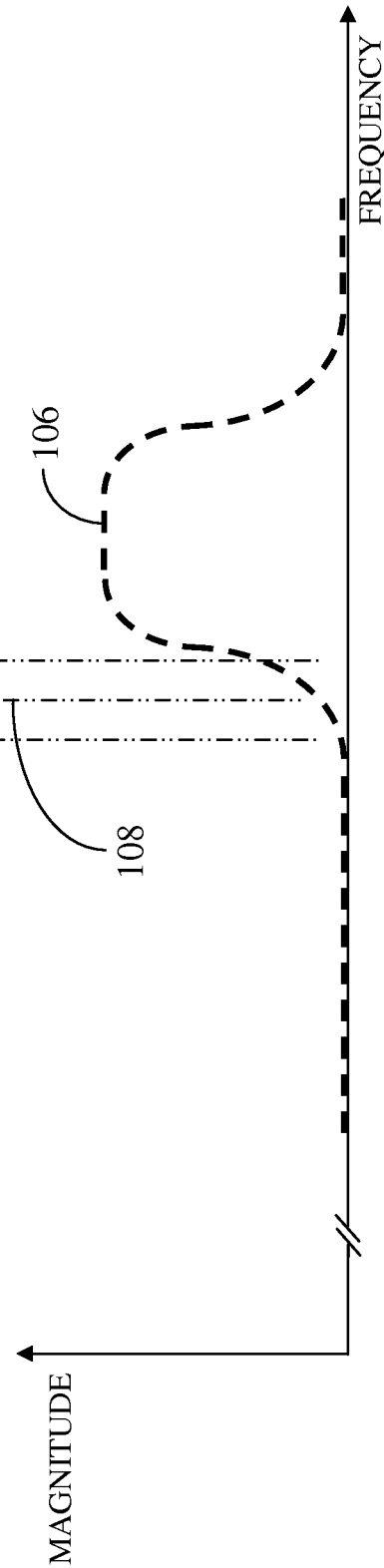
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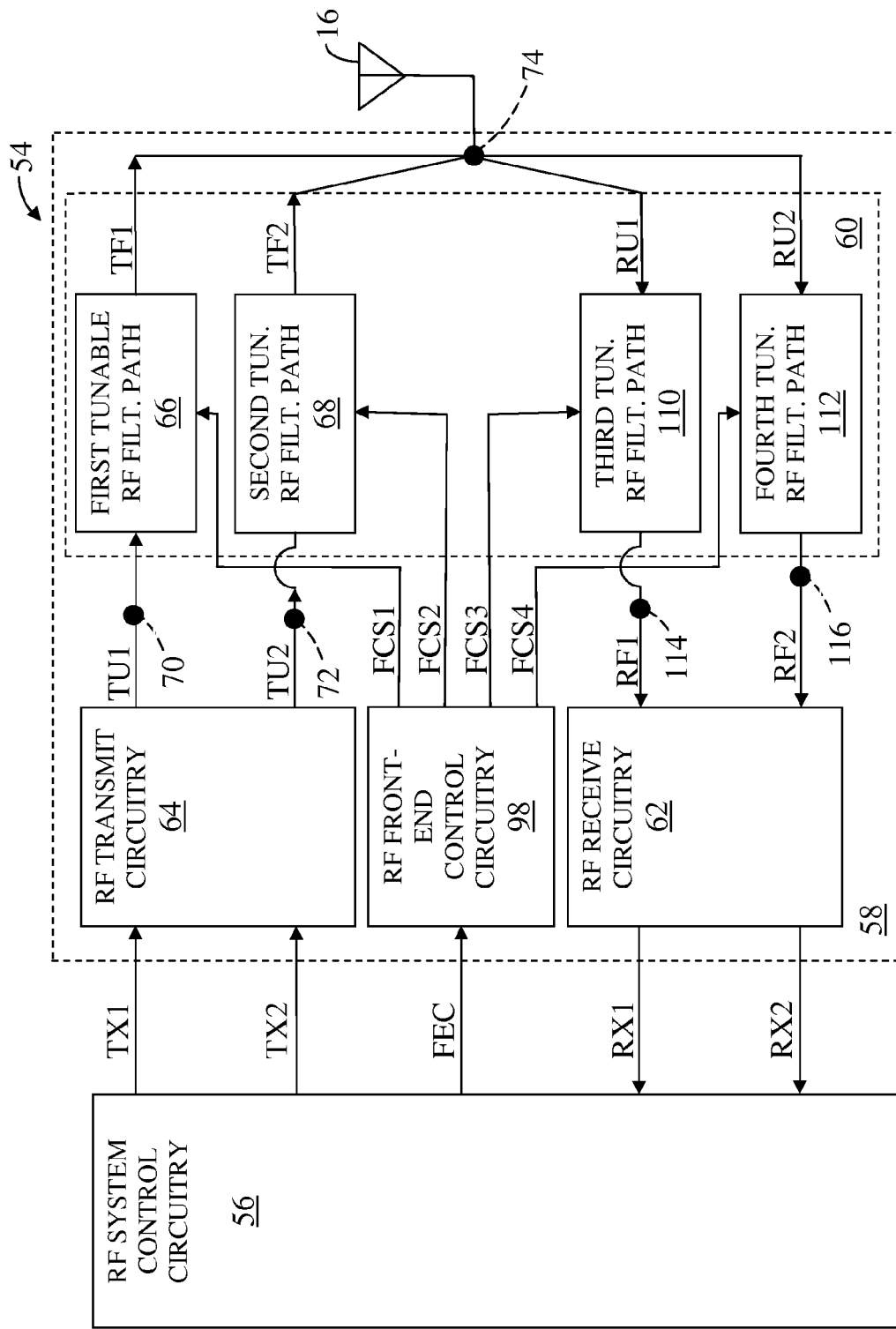
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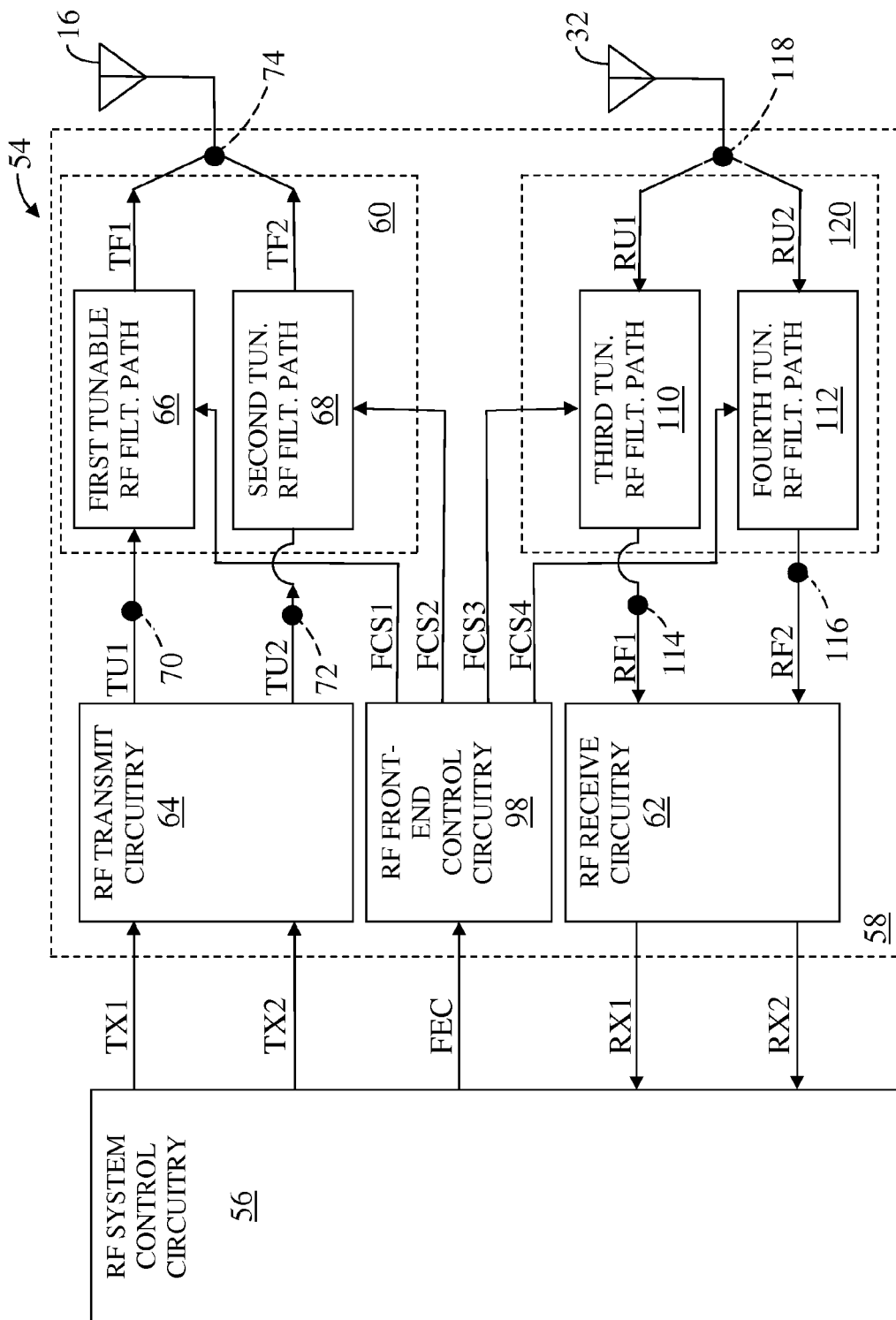
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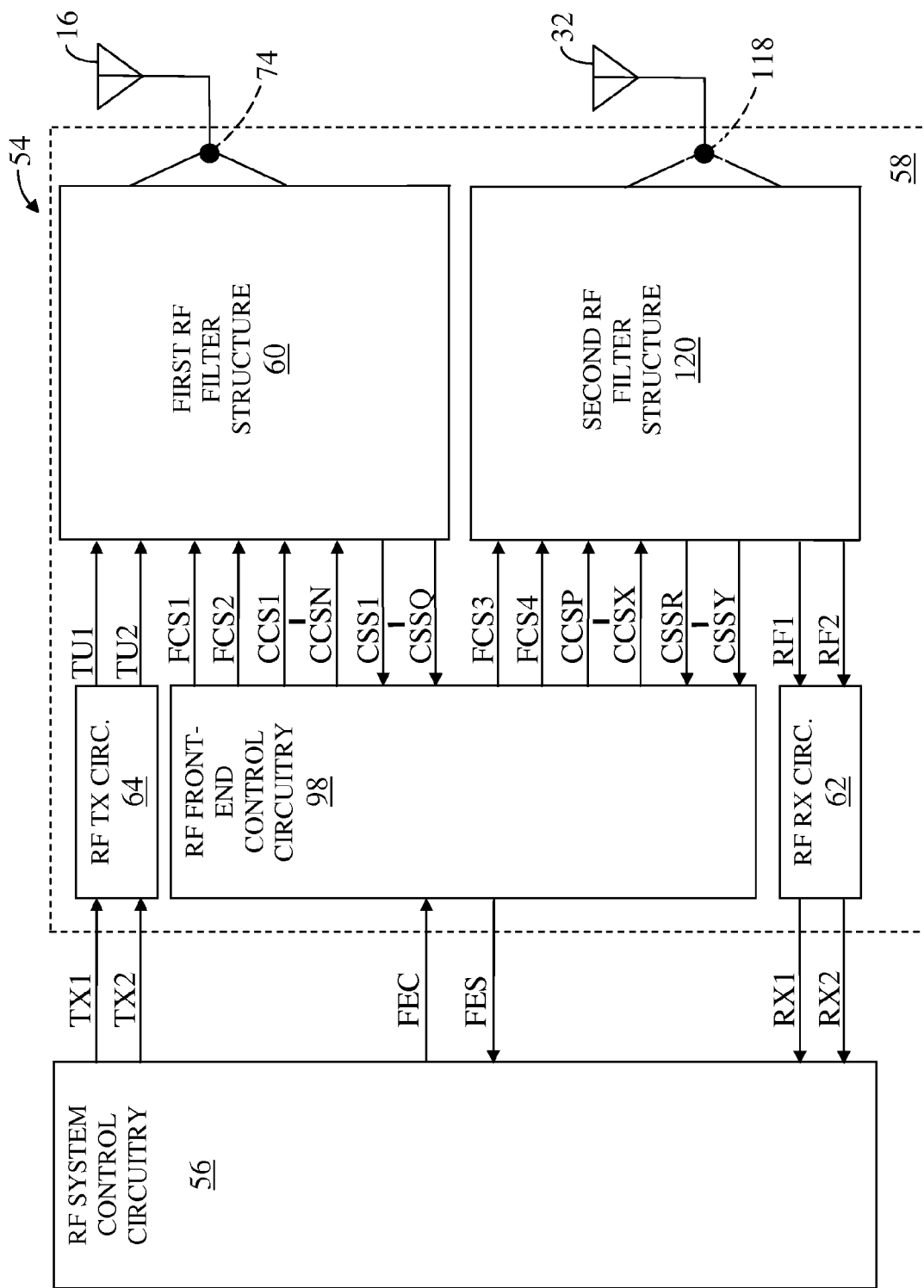
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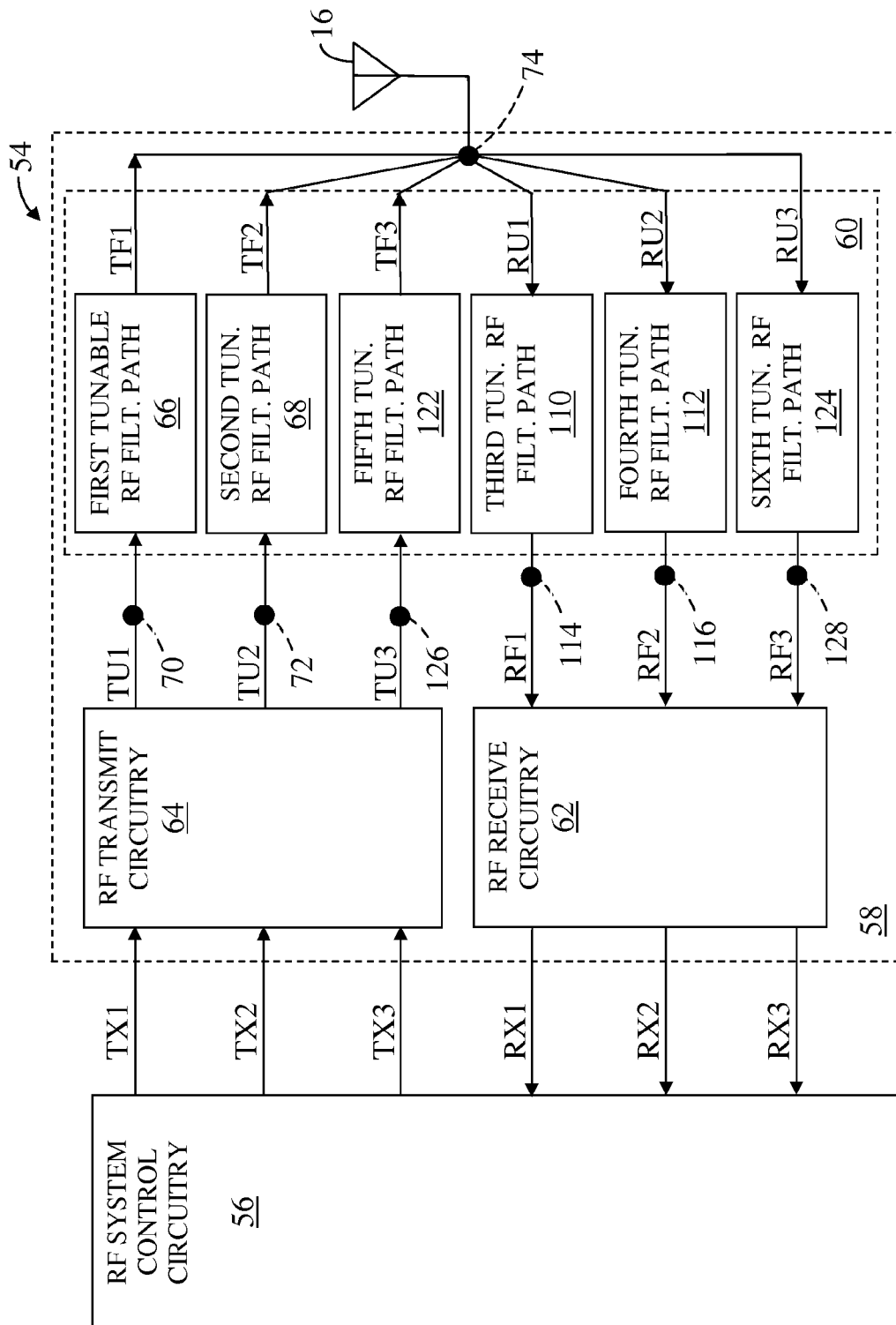
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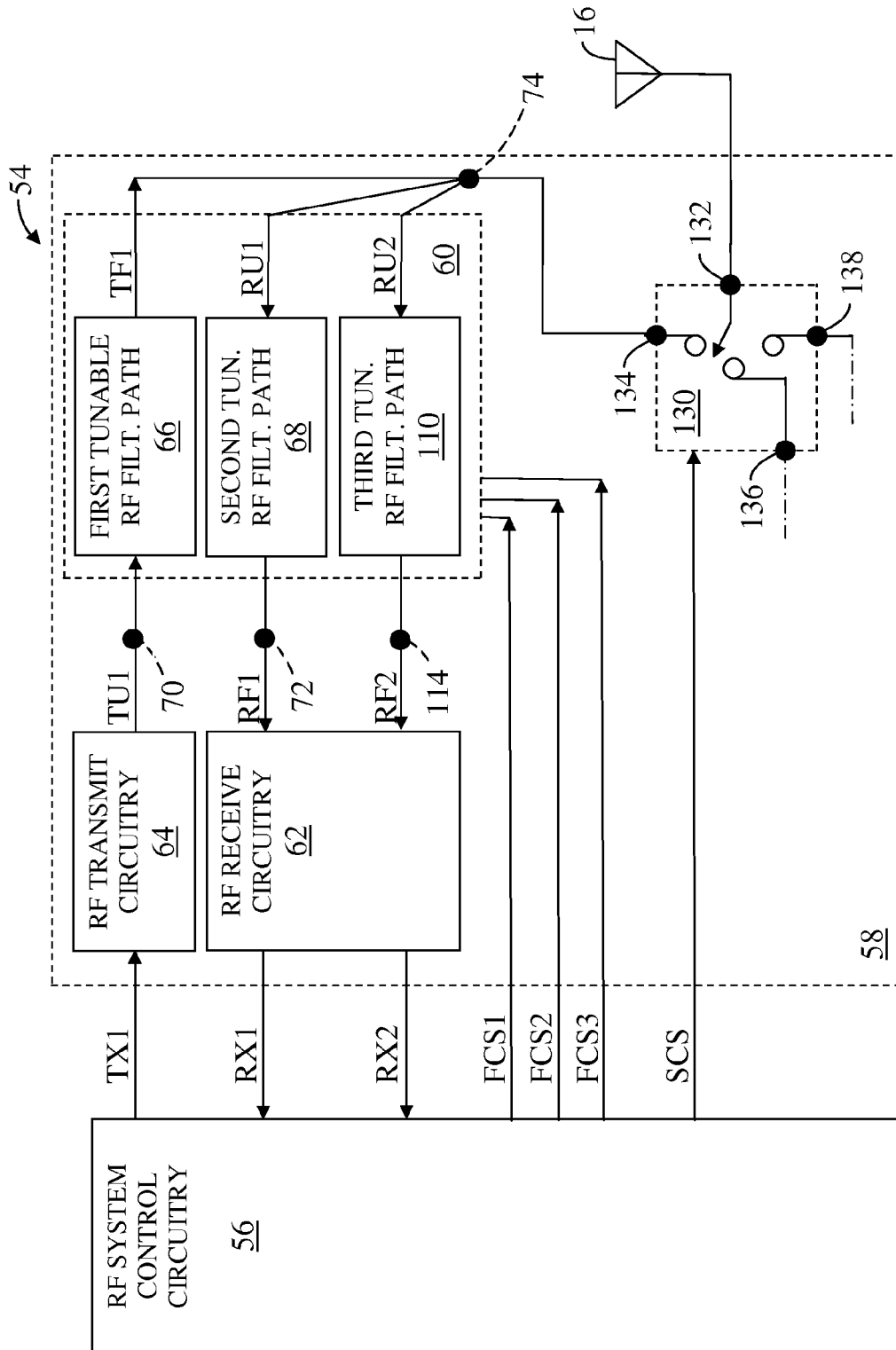
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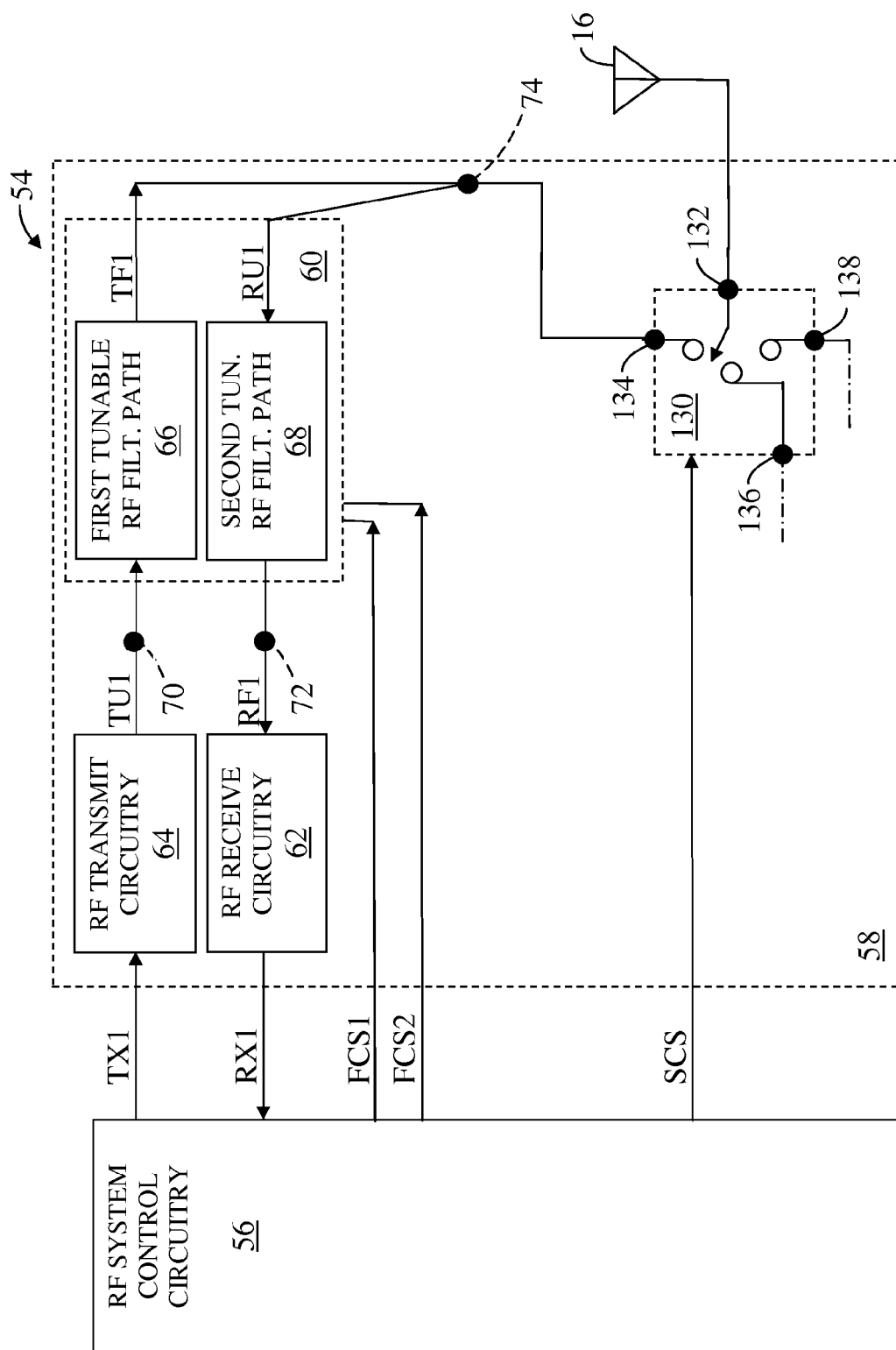
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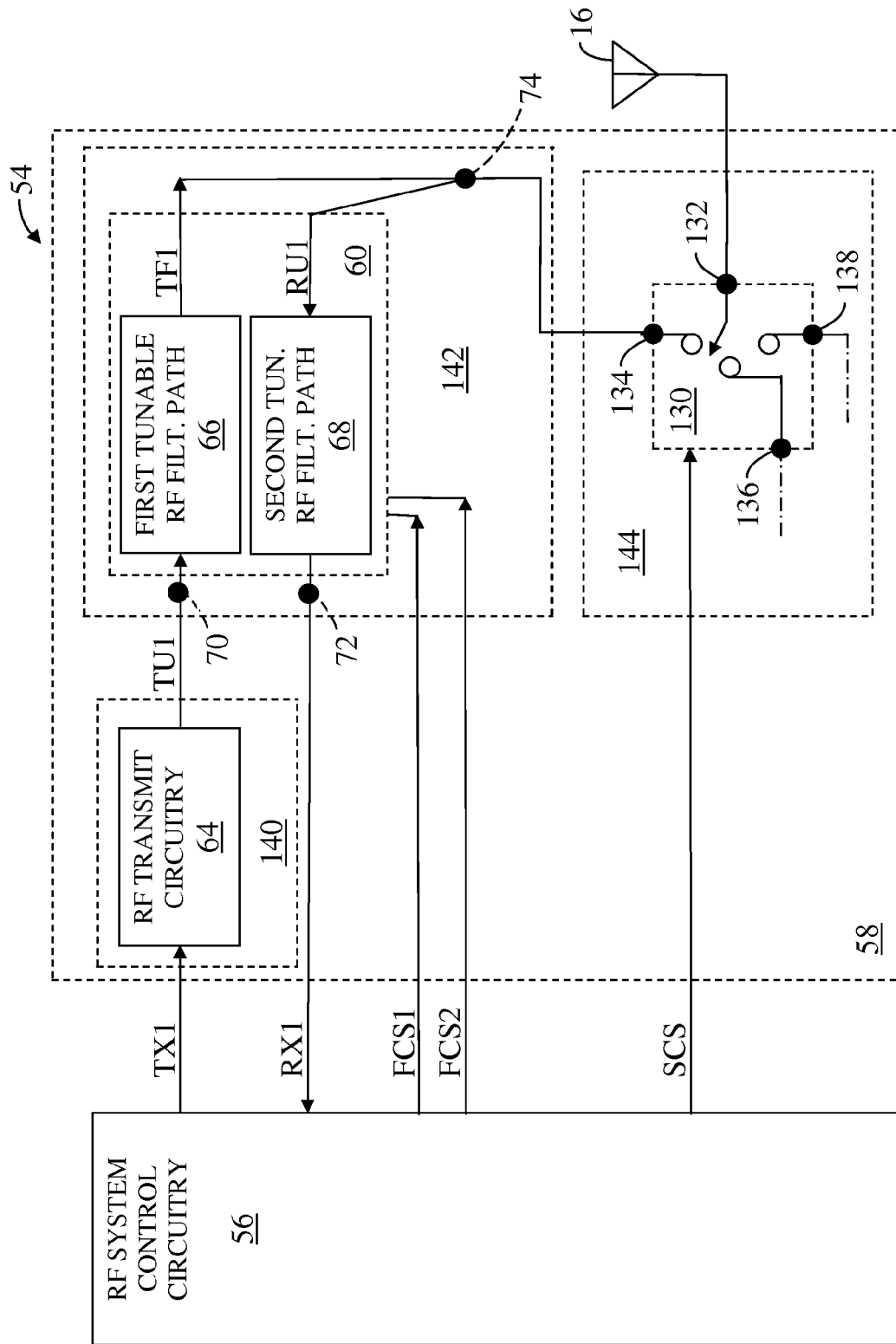
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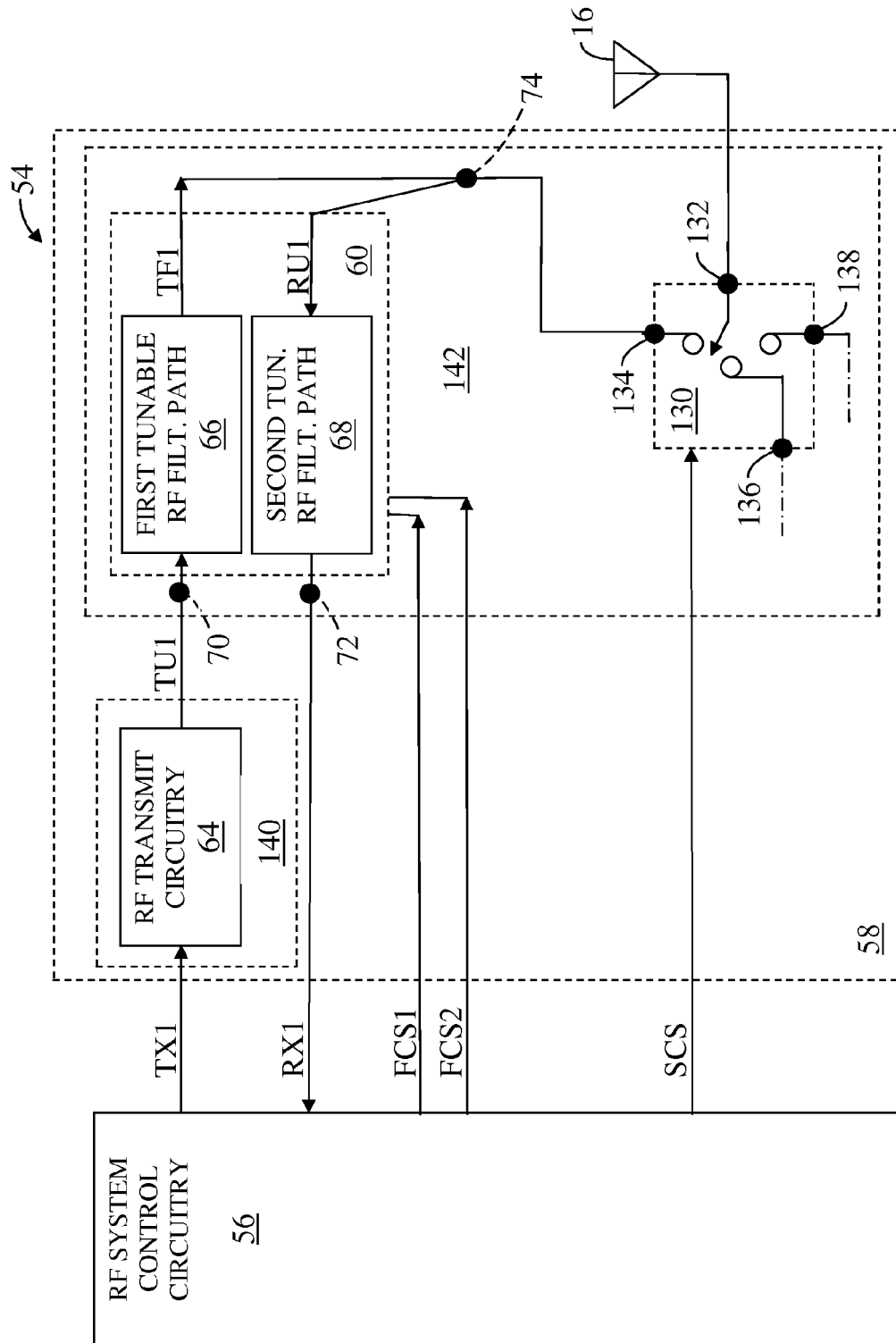
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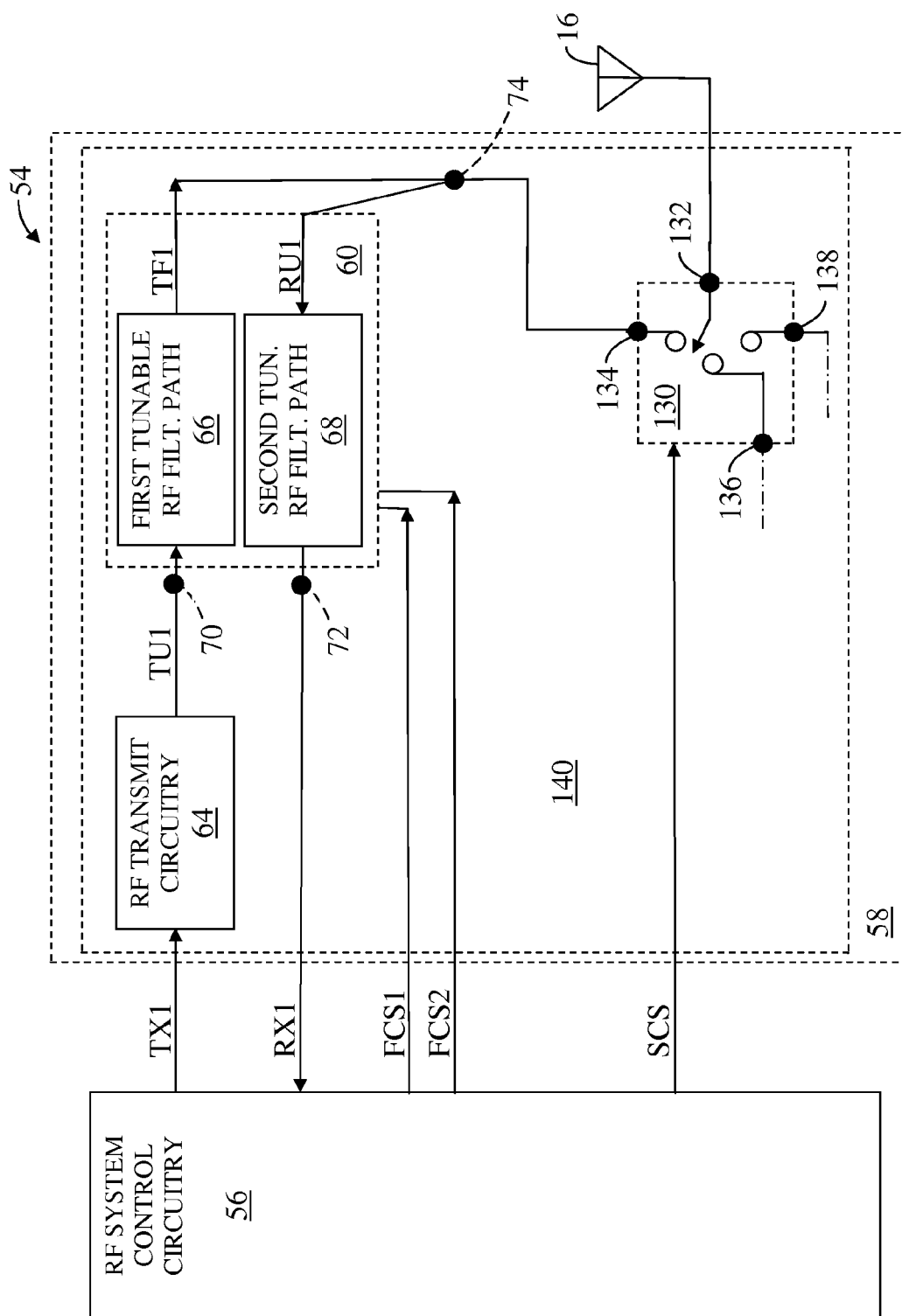
FIG. 19
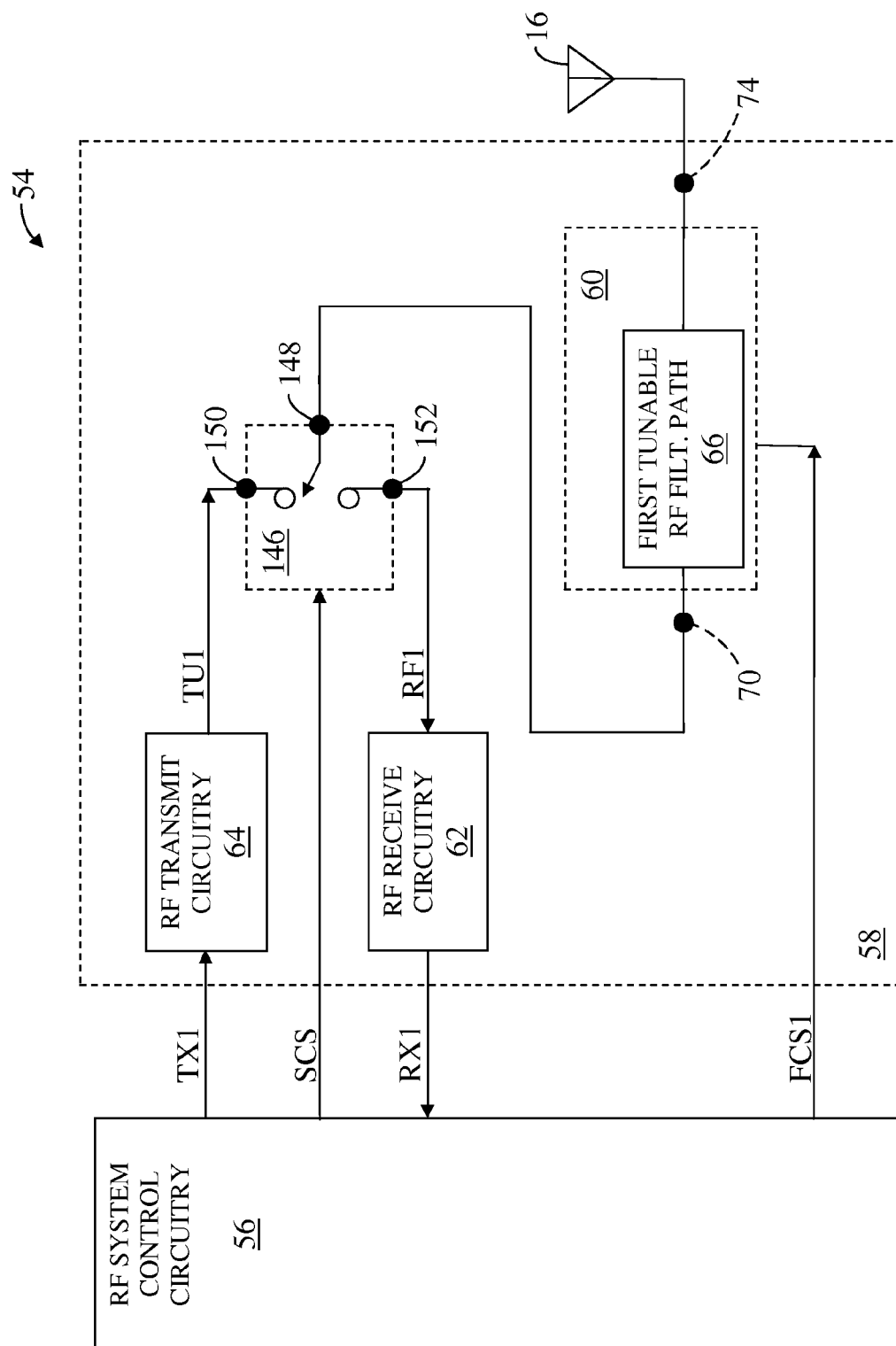
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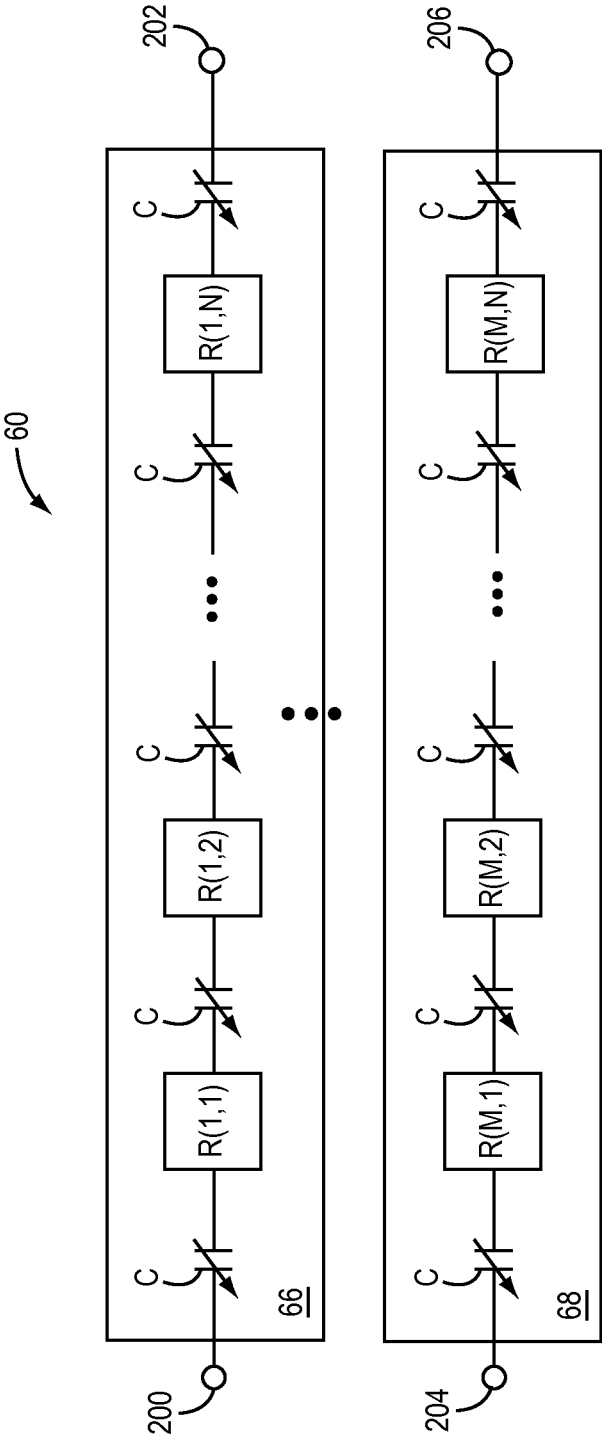
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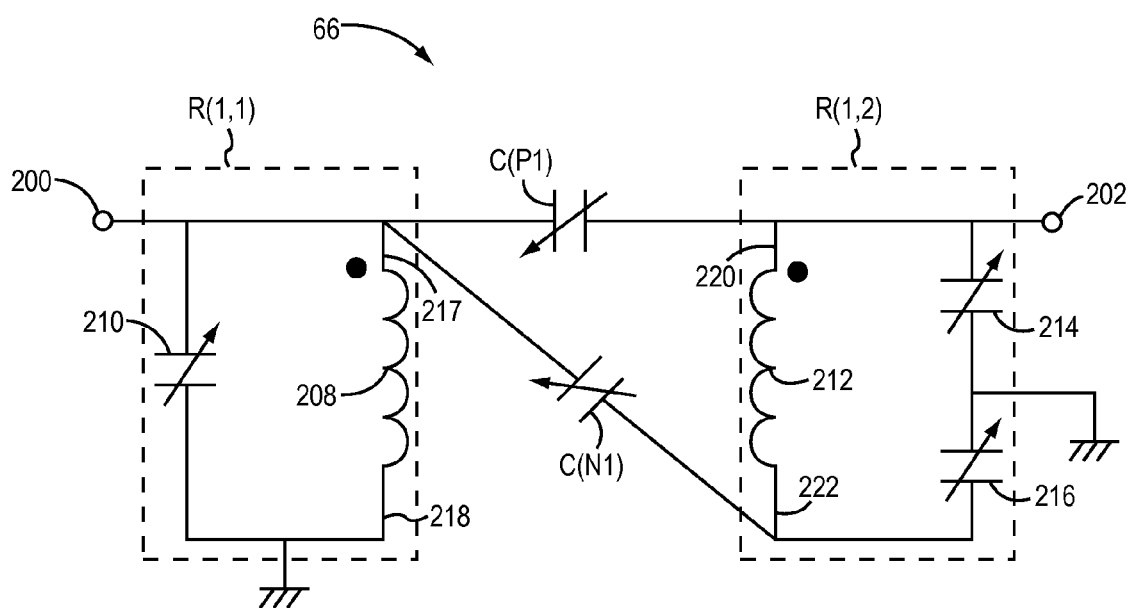
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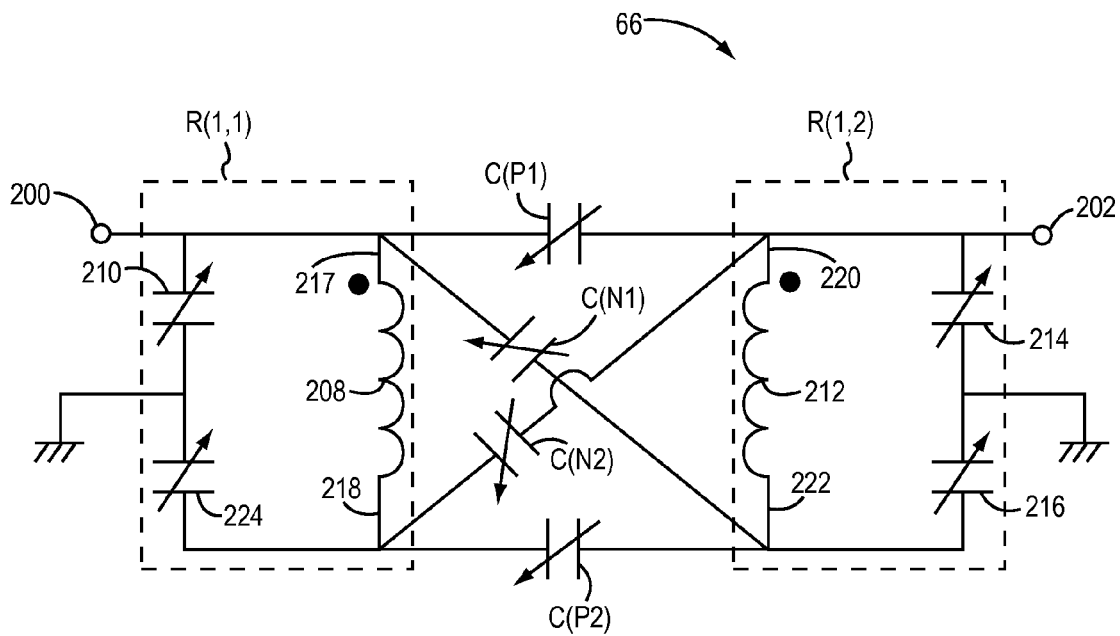
FIG. 23

FIG. 24

FIG. 25

FIG. 26

FIG. 27

IN

TUNABLE FILTER
STRUCTURE
60

OUT_1

• • •

OUT_i

FIG. 28A

IN_1

• • •

IN_j

TUNABLE FILTER
STRUCTURE
60

OUT

FIG. 28B

IN

TUNABLE FILTER STRUCTURE

60

OUT

FIG. 28C

IN_1

TUNABLE FILTER STRUCTURE

60

OUT_1

• • •

• • •

IN_j

OUT_i
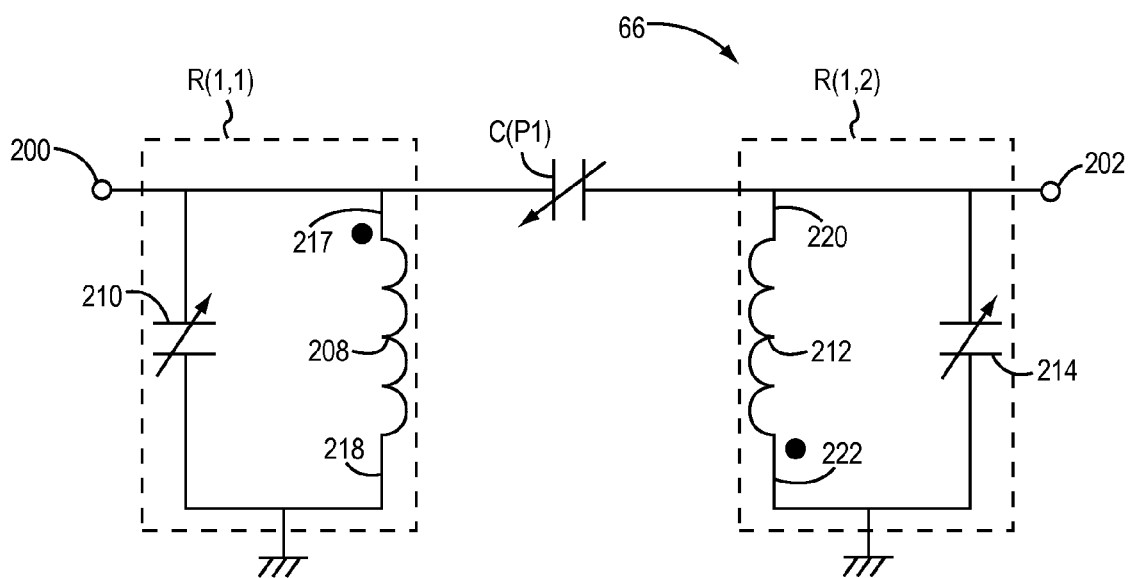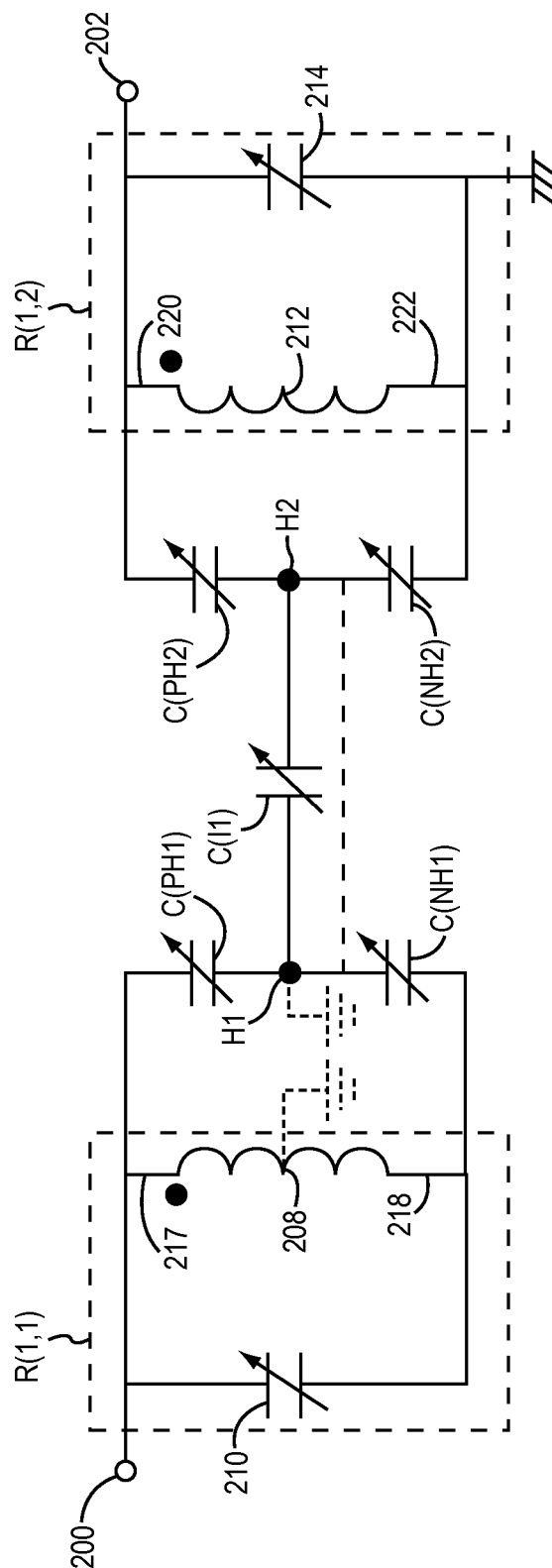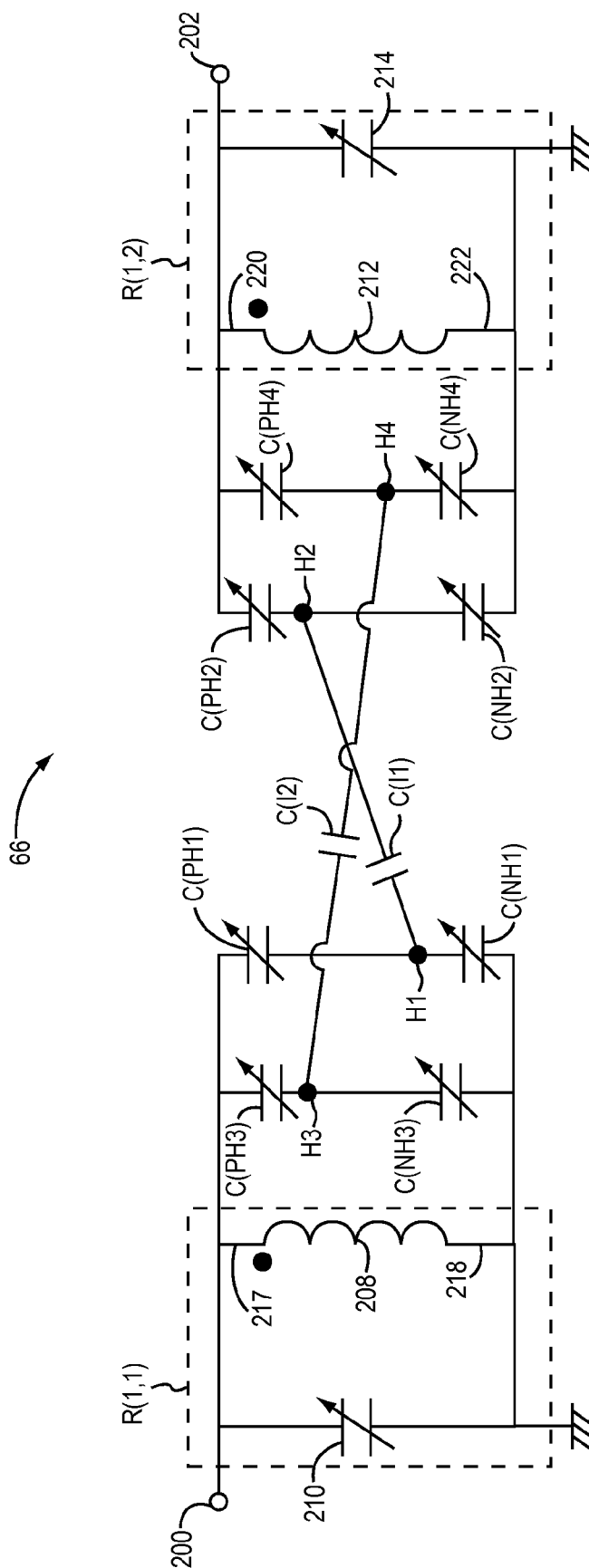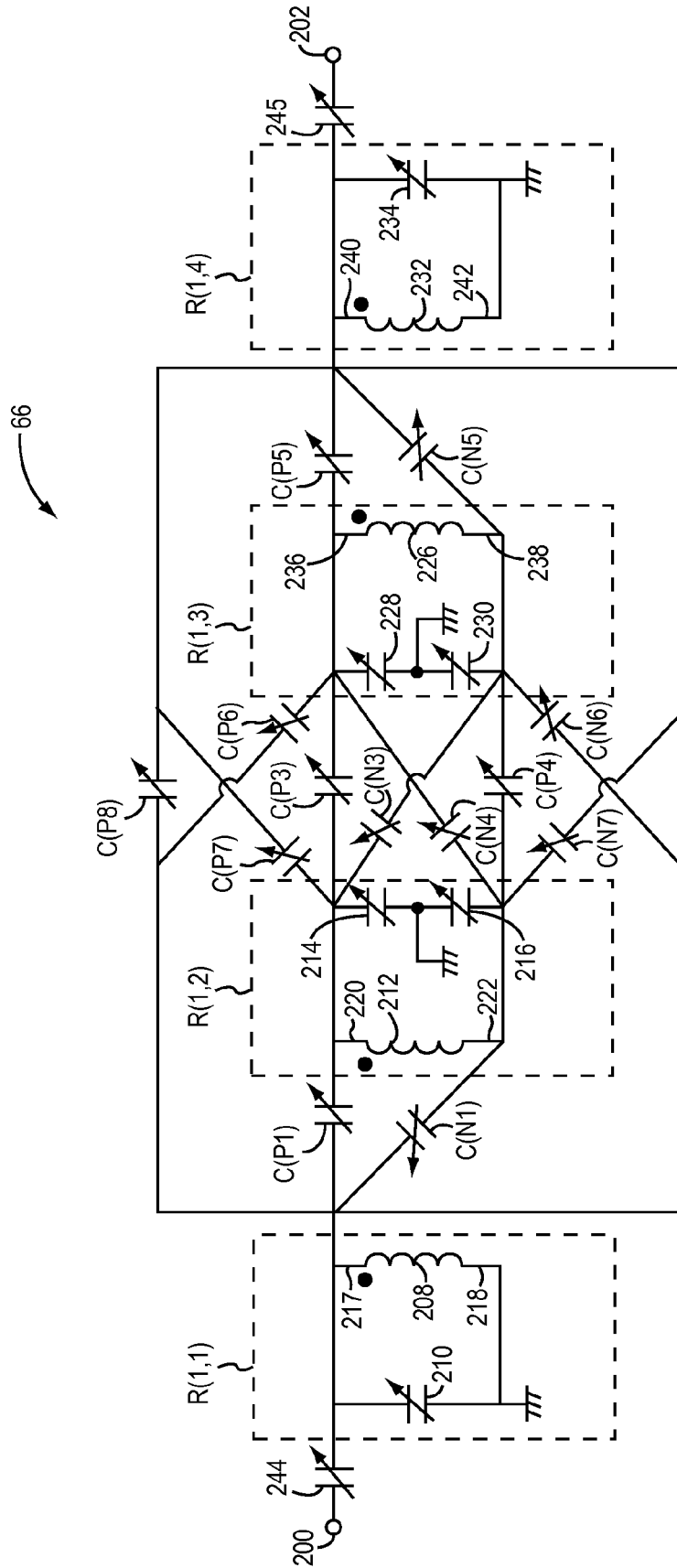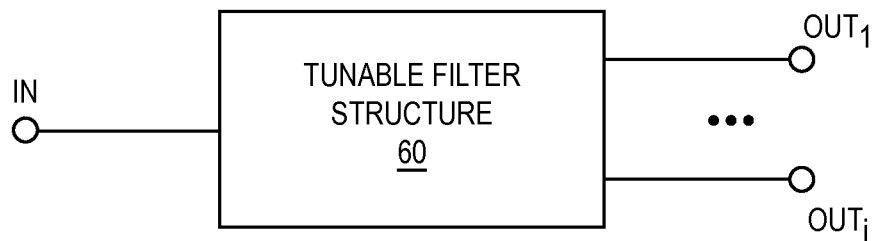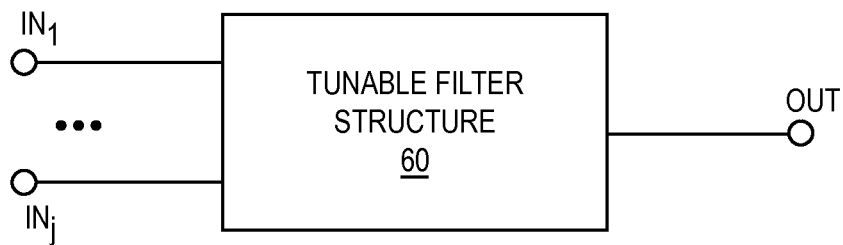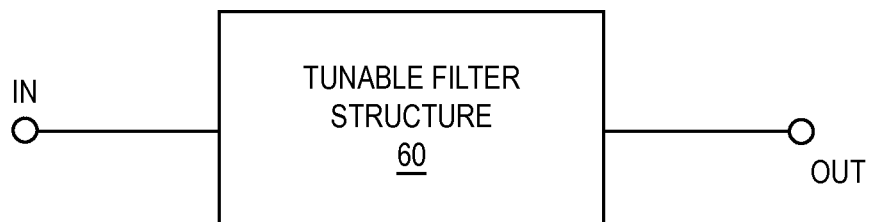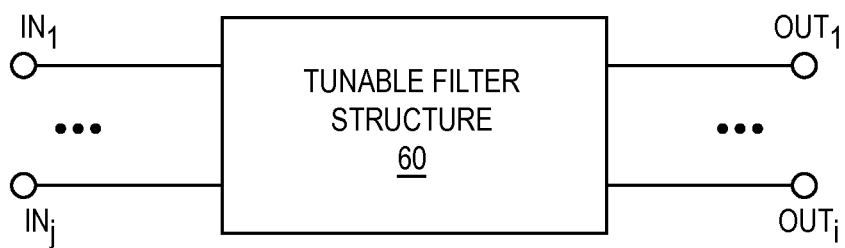
FIG. 28D

FIG. 29

FIG. 30

FIG. 31

FIG. 32

FIG. 33

FIG. 34

FIG. 35

FIG. 36

TUNABLE RF FILTER PATHS FOR TUNABLE RF FILTER STRUCTURES

RELATED APPLICATIONS

The present application claims priority to U.S. Provisional Patent Application No. 61/831,666, filed Jun. 6, 2013; U.S. Provisional Patent Application No. 61/860,932, filed Aug. 1, 2013; U.S. Provisional Patent Application No. 61/909,028, filed Nov. 26, 2013; U.S. Provisional Patent Application No. 61/938,884, filed Feb. 12, 2014; U.S. Provisional Patent Application No. 61/949,581, filed Mar. 7, 2014; U.S. Provisional Patent Application No. 61/951,844, filed Mar. 12, 2014; U.S. Provisional Patent Application No. 61/982,946, filed Apr. 23, 2014; U.S. Provisional Patent Application No. 61/982,952, filed Apr. 23, 2014; U.S. Provisional Patent Application No. 61/982,971, filed Apr. 23, 2014; and U.S. Provisional Patent Application No. 62/008,192, filed Jun. 5, 2014.

The present application is related to concurrently filed U.S. patent application Ser. No. 14/298,829, entitled "TUNABLE RF FILTER STRUCTURE FORMED BY A MATRIX OF WEAKLY COUPLED RESONATORS;" concurrently filed U.S. patent application Ser. No. 14/298,834, entitled "HIGH QUALITY FACTOR INTERCONNECT FOR RF CIRCUITS;" concurrently filed U.S. patent application Ser. No. 14/298,872, entitled "NONLINEAR CAPACITANCE LINEARIZATION;" concurrently filed U.S. patent application Ser. No. 14/298,863, entitled "TUNABLE RF FILTER BASED RF COMMUNICATIONS SYSTEM;" and concurrently filed U.S. patent application Ser. No. 14/298,852, entitled "MULTI-BAND INTERFERENCE OPTIMIZATION."

All of the applications listed above are hereby incorporated herein by reference in their entireties.

FIELD OF THE DISCLOSURE

Embodiments of the present disclosure relate to radio frequency (RF) communications systems, which may include RF front-end circuitry, RF transceiver circuitry, RF amplifiers, direct current (DC)-DC converters, RF filters, RF antennas, RF switches, RF combiners, RF splitters, the like, or any combination thereof.

BACKGROUND

As wireless communications technologies evolve, wireless communications systems become increasingly sophisticated. As such, wireless communications protocols continue to expand and change to take advantage of the technological evolution. As a result, to maximize flexibility, many wireless communications devices must be capable of supporting any number of wireless communications protocols, each of which may have certain performance requirements, such as specific out-of-band emissions requirements, linearity requirements, or the like. Further, portable wireless communications devices are typically battery powered and need to be relatively small, and have low cost. As such, to minimize size, cost, and power consumption, RF circuitry in such a device needs to be as simple, small, flexible, and efficient as is practical. Thus, there is a need for RF circuitry in a communications device that is low cost, small, simple, flexible, and efficient.

SUMMARY

This disclosure relates generally to radio frequency (RF) filter structures. In one embodiment, an RF filter structure is

provided that includes a first resonator and a second resonator. The first resonator and the second resonator are weakly coupled to one another. In this embodiment, the second resonator is op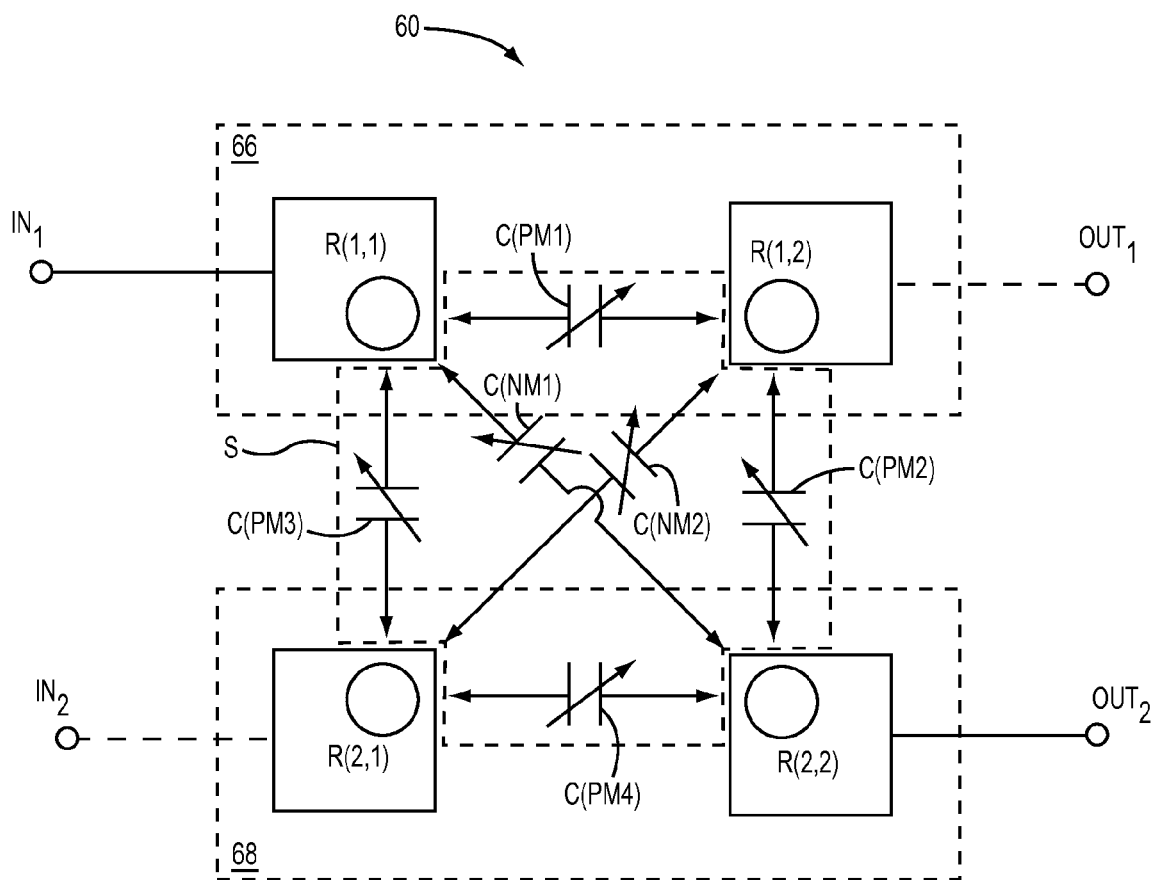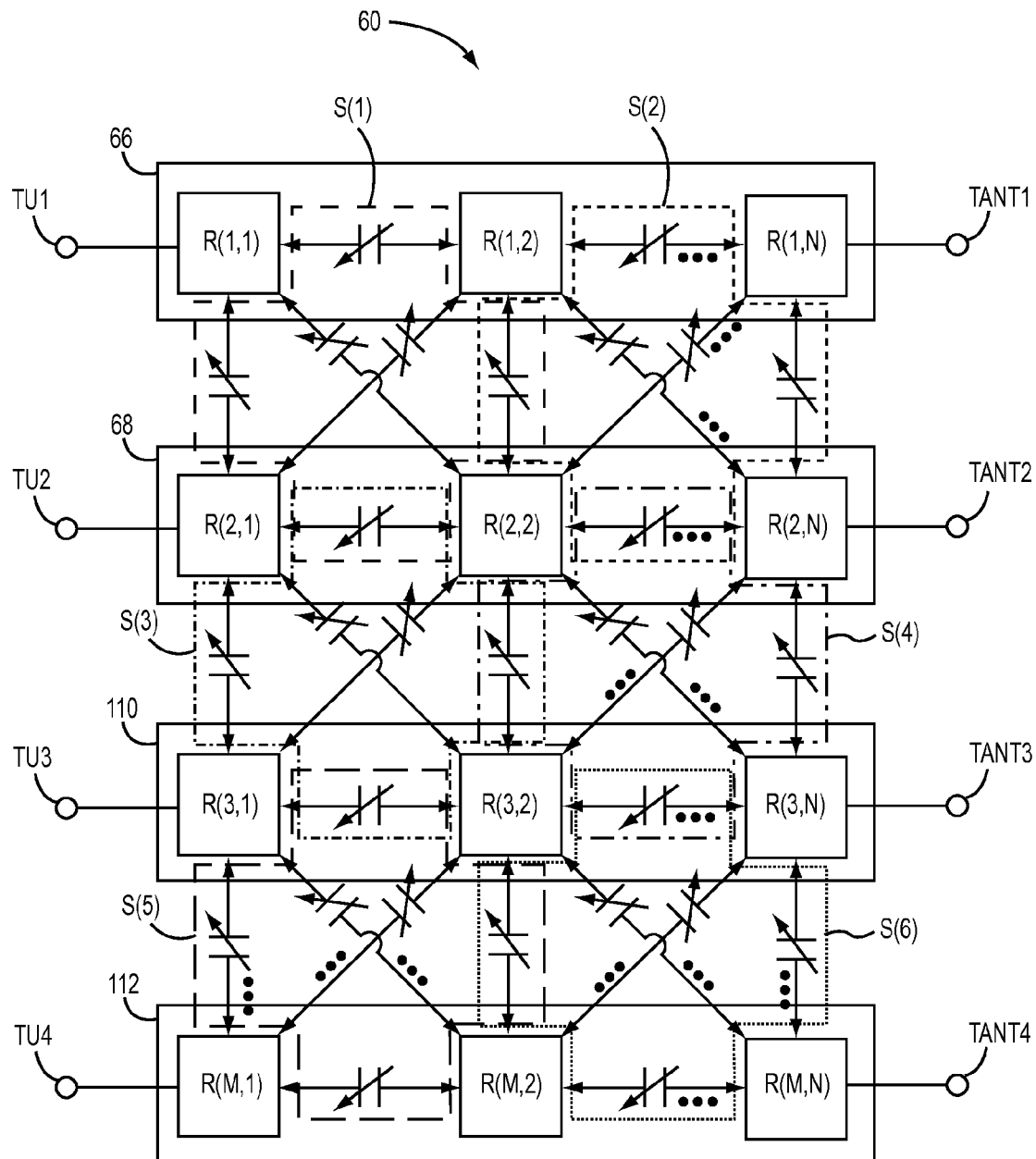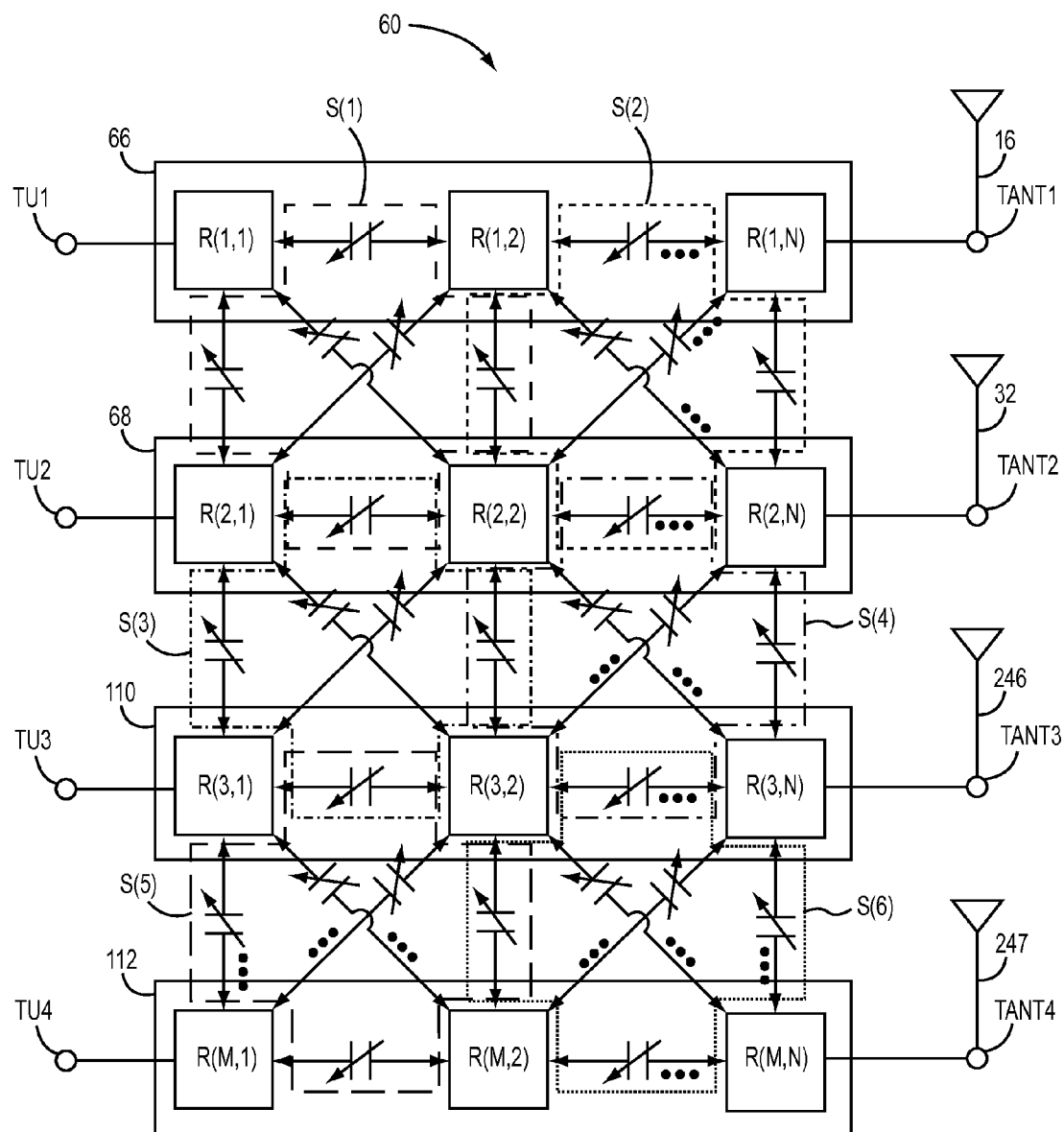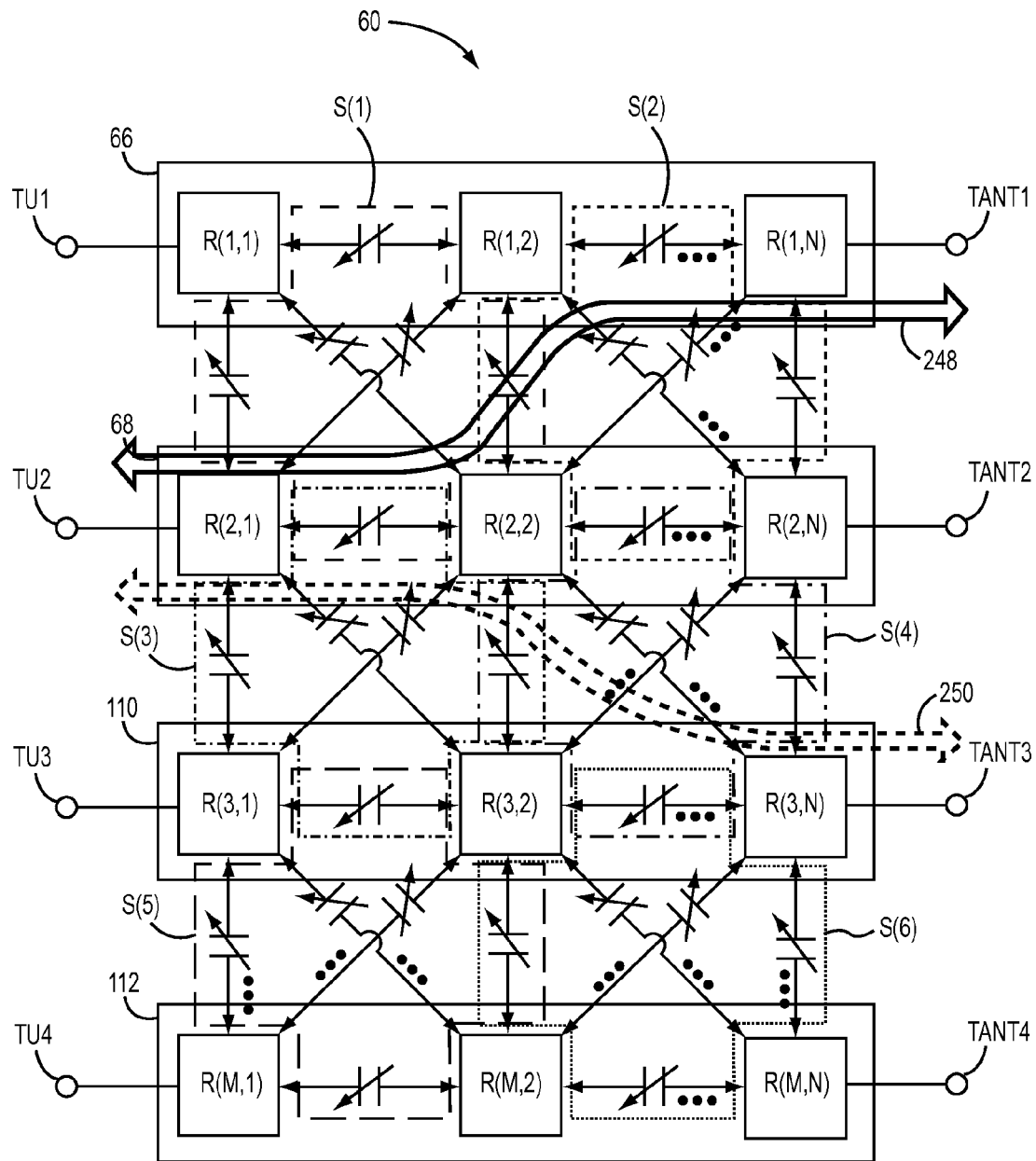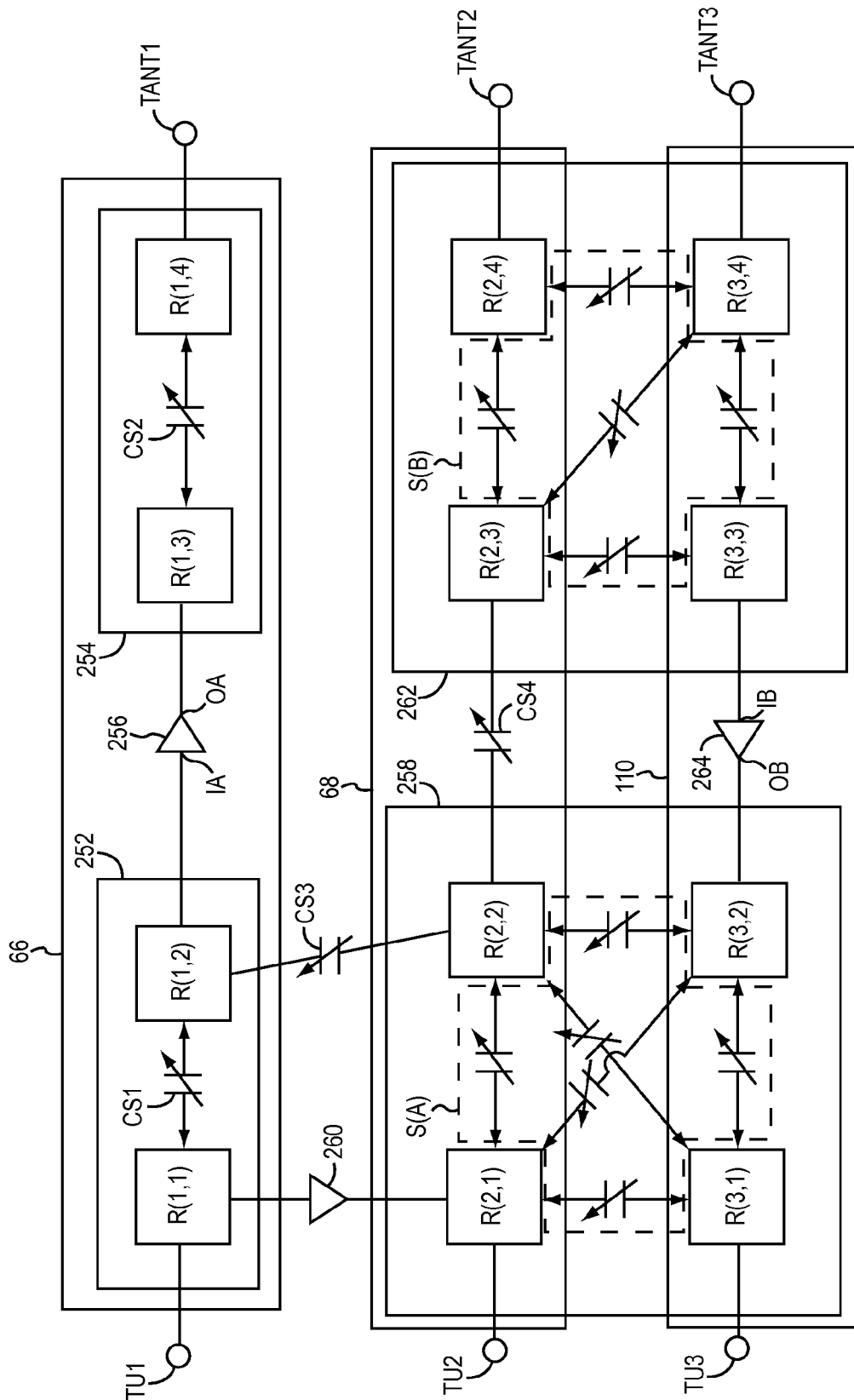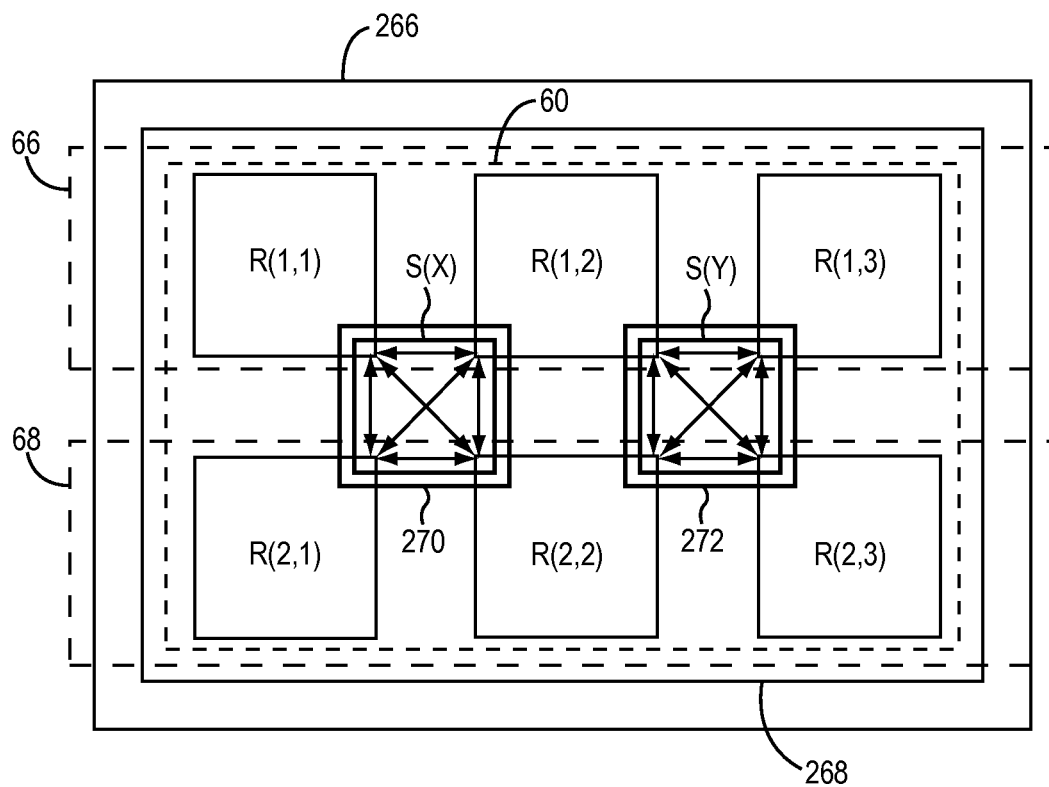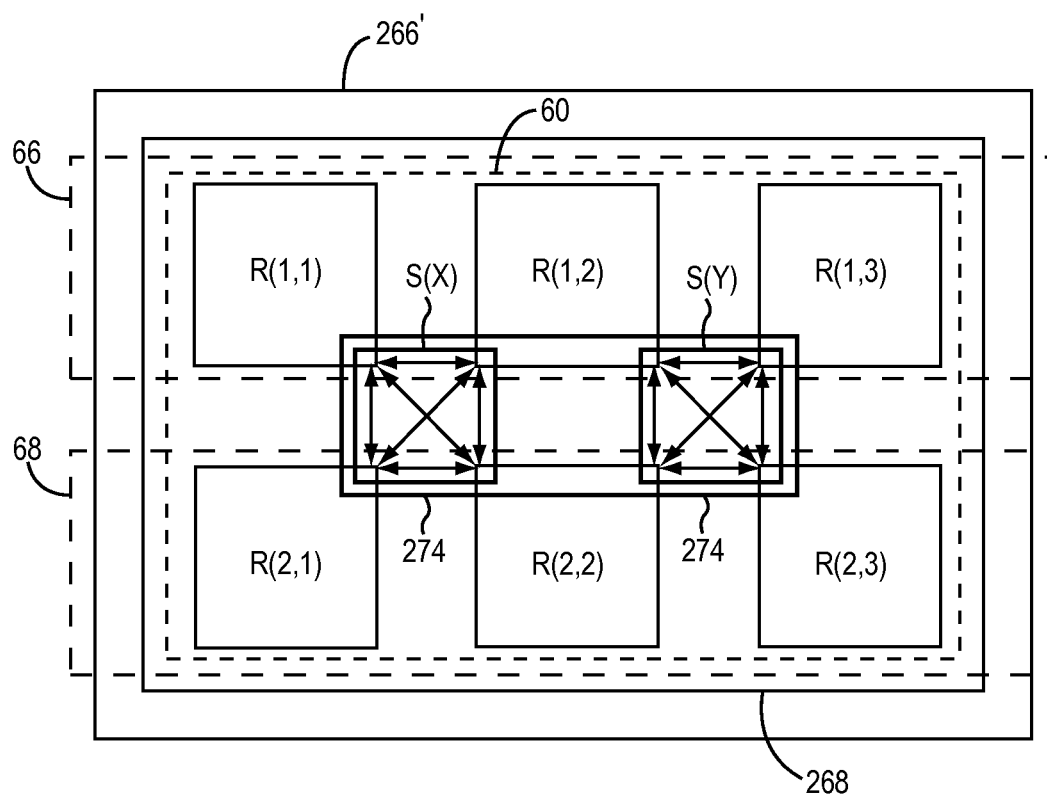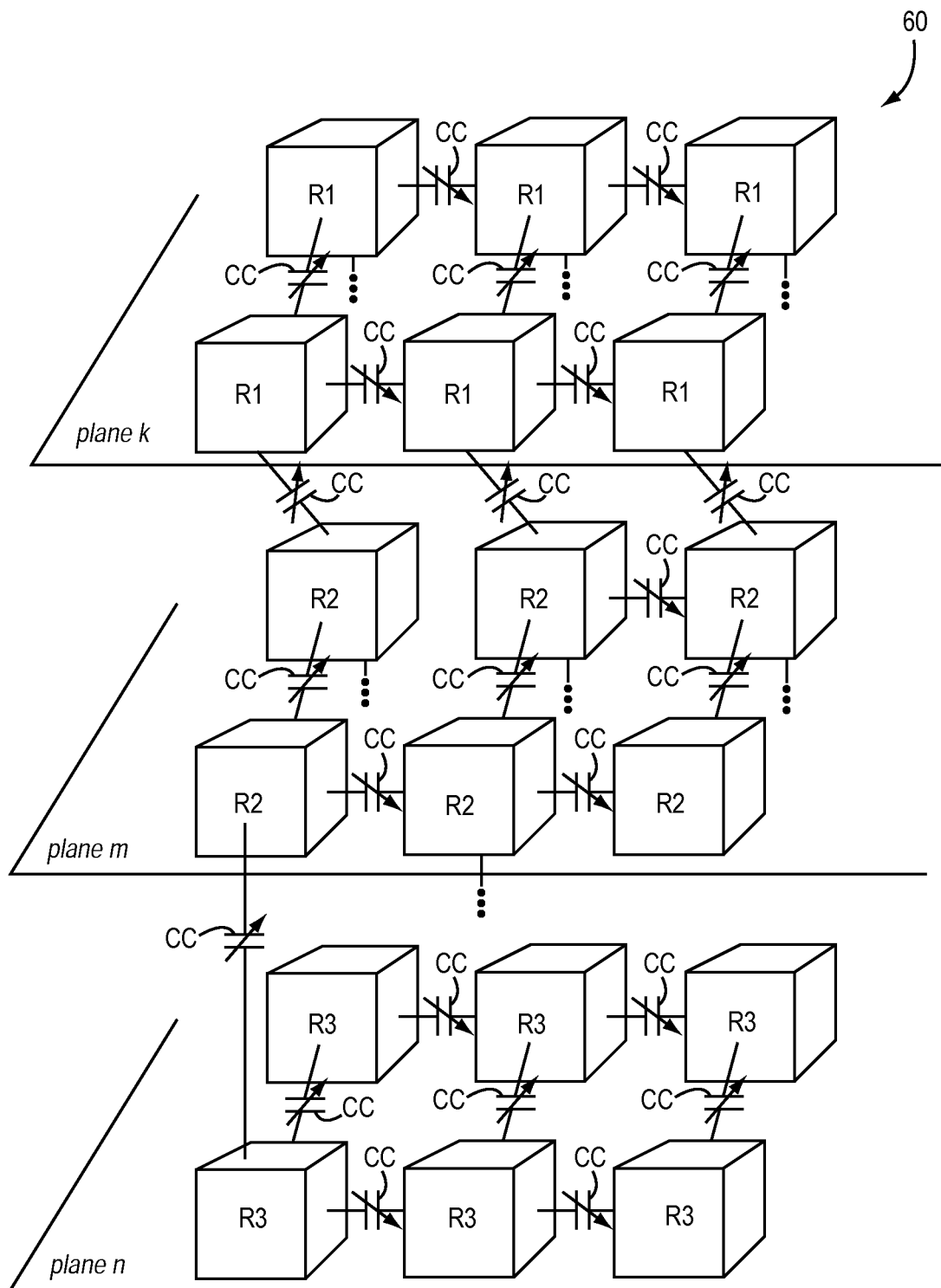erably associated with the first resonator such that an energy transfer factor between the first resonator and the second resonator is less than 10%. The first resonator includes a first inductor and a first capacitive structure electrically connected to the first inductor, while the second resonator has a second inductor and a second capacitive structure electrically connected to the second inductor. The second inductor of the second resonator has a maximum lateral width. A displacement between the first inductor and the second inductor is less than or equal to half the maximum lateral width of the second inductor. Thus, the first inductor and the second inductor are in relatively close proximity. In order to set an electric coupling coefficient between the first resonator and the second resonator, a first cross-coupling capacitive structure is electrically connected between the first resonator and the second resonator.

Those skilled in the art will appreciate the scope of the present disclosure and realize additional aspects thereof after reading the following detailed description of the preferred embodiments in association with the accompanying drawing figures.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings incorporated in and forming a part of this specification illustrate several aspects of the disclosure, and together with the description serve to explain the principles of the disclosure.

FIG. 1 shows traditional communications circuitry according to the prior art.

FIG. 2 shows the traditional communications circuitry according to the prior art.

FIG. 3 shows the traditional communications circuitry according to the prior art.

FIG. 4 shows RF communications circuitry according to one embodiment of the RF communications circuitry.

FIG. 5 is a graph illustrating filtering characteristics of a first tunable RF filter path and a second tunable RF filter path illustrated in FIG. 4 according to one embodiment of the first tunable RF filter path and the second tunable RF filter path.

FIGS. 6A and 6B are graphs illustrating filtering characteristics of the first tunable RF filter path and the second tunable RF filter path, respectively, illustrated in FIG. 4 according to an alternate embodiment of the first tunable RF filter path and the second tunable RF filter path, respectively.

FIG. 7 shows the RF communications circuitry according to one embodiment of the RF communications circuitry.

FIG. 8 shows the RF communications circuitry according to an alternate embodiment of the RF communications circuitry.

FIGS. 9A and 9B are graphs illustrating filtering characteristics of the first tunable RF filter path and the second tunable RF filter path, respectively, illustrated in FIG. 8 according to an additional embodiment of the first tunable RF filter path and the second tunable RF filter path.

FIGS. 10A and 10B are graphs illustrating filtering characteristics of a first traditional RF duplexer and a second traditional RF duplexer, respectively, illustrated in FIG. 3 according to the prior art.

FIG. 11 shows the RF communications circuitry according to one embodiment of the RF communications circuitry.

FIG. 12 shows the RF communications circuitry according to an alternate embodiment of the RF communications circuitry.

FIG. 13 shows the RF communications circuitry according to an additional embodiment of the RF communications circuitry.

FIG. 14 shows the RF communications circuitry according to another embodiment of the RF communications circuitry.

FIG. 15 shows the RF communications circuitry according to a further embodiment of the RF communications circuitry.

FIG. 16 shows the RF communications circuitry according to one embodiment of the RF communications circuitry.

FIG. 17 shows the RF communications circuitry according to an alternate embodiment of the RF communications circuitry.

FIG. 18 shows the RF communications circuitry according to an additional embodiment of the RF communications circuitry.

FIG. 19 shows the RF communications circuitry according to another embodiment of the RF communications circuitry.

FIG. 20 shows the RF communications circuitry according to a further embodiment of the RF communications circuitry.

FIG. 21 illustrates one embodiment of a tunable radio frequency (RF) filter structure that defines multiple tunable RF filtering paths that are independent of each other.

FIG. 22 illustrates one embodiment of a tunable RF filter path shown in FIG. 21 having cross-coupling capacitors arranged in a V-bridge structure.

FIG. 23 illustrates another embodiment of the tunable RF filter path shown in FIG. 21 having cross-coupling capacitors arranged in an X-bridge structure.

FIG. 24 illustrates another embodiment of the tunable RF filter path shown in FIG. 21 having a cross-coupling capacitor arranged in a single positive bridge structure.

FIG. 25 illustrates another embodiment of the tunable RF filter path shown in FIG. 21 having cross-coupling capacitors arranged in an H-bridge structure.

FIG. 26 illustrates another embodiment of the tunable RF filter path shown in FIG. 21 having cross-coupling capacitors arranged in a double H-bridge structure.

FIG. 27 illustrates another embodiment of the tunable RF filter path shown in FIG. 21 having four weakly coupled resonators with magnetic and electric couplings between them.

FIGS. 28A-28D disclose different embodiments of a tunable RF filter structure, each with a different number of input terminals and output terminals.

FIG. 29 illustrates one embodiment of a tunable radio frequency (RF) filter structure having four resonators and cross-coupling capacitive structures electrically connected between the four resonators so as to form a 2×2 matrix with the four resonators. In alternative embodiments, fewer (e.g., three) resonators or more (e.g., five or more) resonators may be provided.

FIG. 30 illustrates another embodiment of a tunable RF filter structure having M number of rows and N number of columns of resonators that are electrically connected by cross-coupling capacitive structures so that the tunable RF filter structure is arranged so as to form an M×N two-dimensional matrix of the resonators.

FIG. 31 illustrates the tunable RF filter structure shown in FIG. 30 electrically connected to various RF antennas.

FIG. 32 illustrates the tunable RF filter structure shown in FIG. 30 with two tunable RF filter paths highlighted for performing Multiple Input Multiple Output (MIMO), Single Input Multiple Output (SIMO), Multiple Input Single Output (MISO), and Single Input Single Output (SISO) operations.

FIG. 33 illustrates another embodiment of a tunable RF filter structure with amplifier stages electrically connected within and between tunable RF filter paths.

FIG. 34 illustrates an embodiment of a tunable RF filter structure integrated into an integrated circuit (IC) package with multiple and separate semiconductor dies.

FIG. 35 illustrates an embodiment of the same tunable RF filter structure shown in FIG. 34, but now integrated into an IC package with a single semiconductor die.

FIG. 36 illustrates one embodiment of a tunable RF filter structure having resonators and cross-coupling capacitive structures electrically connected between the resonators so as to form a three-dimensional matrix of the resonators.

DETAILED DESCRIPTION

The embodiments set forth below represent the necessary information to enable those skilled in the art to practice the disclosure and illustrate the best mode of practicing the disclosure. Upon reading the following description in light of the accompanying drawings, those skilled in the art will understand the concepts of the disclosure and will recognize applications of these concepts not particularly addressed herein. It should be understood that these concepts and applications fall within the scope of the disclosure and the accompanying claims.

RF communications circuitry, which includes a first RF filter structure, is disclosed according to a first embodiment of the present disclosure. The first RF filter structure includes a first tunable RF filter path and a second tunable RF filter path. The first tunable RF filter path includes a pair of weakly coupled resonators. Additionally, a first filter parameter of the first tunable RF filter path is tuned based on a first filter control signal. A first filter parameter of the second tunable RF filter path is tuned based on a second filter control signal.

In one embodiment of the first RF filter structure, the first tunable RF filter path is directly coupled between a first common connection node and a first connection node. The second tunable RF filter path is directly coupled between a second connection node and the first common connection node.

In one embodiment of the RF communications system, the first tunable RF filter path and the second tunable RF filter path do not significantly load one another at frequencies of interest. As such, by directly coupling the first tunable RF filter path and the second tunable RF filter path to the first common connection node; front-end RF switching elements may be avoided, thereby reducing cost, size, and non-linearity; and increasing efficiency and flexibility of the RF communications system. In one embodiment of the RF communications system, the first common connection node is coupled to an antenna.

Embodiments of the RF communications system include frequency division duplex (FDD) applications, time division duplex (TDD) applications, carrier-aggregation (CA) applications, multiple antenna applications, MIMO applications, hybrid applications, applications supporting multiple communications bands, the like, or any combination thereof.

FIG. 1 shows traditional communications circuitry 10 according to the prior art. The traditional communications circuitry 10 illustrated in FIG. 1 is a time-division duplex (TDD) system, which is capable of transmitting and receiving RF signals, but not simultaneously. Such a system may also be called a half-duplex system. Additionally, the traditional communications circuitry 10 may be used as a simplex system, which is a system that only transmits RF signals or only receives RF signals. Traditional communications systems often use fixed frequency filters. As a result, to cover multiple communications bands, switching elements are needed to select between different signal paths.

The traditional communications circuitry **10** includes traditional RF system control circuitry **12**, traditional RF front-end circuitry **14**, and a first RF antenna **16**. The traditional RF front-end circuitry **14** includes traditional RF front-end control circuitry **18**, first traditional antenna matching circuitry **20**, first traditional RF receive circuitry **22**, first traditional RF transmit circuitry **24**, a first traditional RF switch **26**, and a second traditional RF switch **28**. The first traditional RF switch **26** is coupled between the first traditional antenna matching circuitry **20** and the first traditional RF receive circuitry **22**. The second traditional RF switch **28** is coupled between the first traditional antenna matching circuitry **20** and the first traditional RF transmit circuitry **24**. The first RF antenna **16** is coupled to the first traditional antenna matching circuitry **20**. The first traditional antenna matching circuitry **20** provides at least partial impedance matching between the first RF antenna **16** and either the first traditional RF receive circuitry **22** or the first traditional RF transmit circuitry **24**.

The traditional RF system control circuitry **12** provides the necessary control functions needed to facilitate RF communications between the traditional communications circuitry **10** and other RF devices. The traditional RF system control circuitry **12** processes baseband signals needed for the RF communications. As such, the traditional RF system control circuitry **12** provides a first traditional upstream transmit signal TUT1 to the first traditional RF transmit circuitry **24**. The first traditional upstream transmit signal TUT1 may be a baseband transmit signal, an intermediate frequency (IF) transmit signal, or an RF transmit signal. Conversely, the traditional RF system control circuitry **12** receives a first traditional downstream receive signal TDR1 from the first traditional RF receive circuitry **22**. The first traditional downstream receive signal TDR1 may be a baseband receive signal, an IF receive signal, or an RF receive signal.

The first traditional RF transmit circuitry **24** may include up-conversion circuitry, amplification circuitry, power supply circuitry, filtering circuitry, switching circuitry, combining circuitry, splitting circuitry, dividing circuitry, clocking circuitry, the like, or any combination thereof. Similarly, the first traditional RF receive circuitry **22** may include down-conversion circuitry, amplification circuitry, power supply circuitry, filtering circuitry, switching circuitry, combining circuitry, splitting circuitry, dividing circuitry, clocking circuitry, the like, or any combination thereof.

The traditional RF system control circuitry **12** provides a traditional front-end control signal TFEC to the traditional RF front-end control circuitry **18**. The traditional RF front-end control circuitry **18** provides a first traditional switch control signal TCS1 and a second traditional switch control signal TCS2 to the first traditional RF switch **26** and the second traditional RF switch **28**, respectively, based on the traditional front-end control signal TFEC. As such, the traditional RF system control circuitry **12** controls the first traditional RF switch **26** and the second traditional RF switch **28** via the traditional front-end control signal TFEC. The first traditional RF switch **26** is in one of an ON state and an OFF state based on the first traditional switch control signal TCS1. The second traditional RF switch **28** is in one of an ON state and an OFF state based on the second traditional switch control signal TCS2.

Half-duplex operation of the traditional communications circuitry **10** is accomplished using the first traditional RF switch **26** and the second traditional RF switch **28**. When the traditional communications circuitry **10** is transmitting RF signals via the first RF antenna **16**, the first traditional RF switch **26** is in the OFF state and the second traditional RF switch **28** is in the ON state. As such, the first traditional

antenna matching circuitry **20** is electrically isolated from the first traditional RF receive circuitry **22** and the first traditional antenna matching circuitry **20** is electrically coupled to the first traditional RF transmit circuitry **24**. In this regard, the traditional RF system control circuitry **12** provides the first traditional upstream transmit signal TUT1 to the first traditional RF transmit circuitry **24**, which provides a traditional transmit signal TTX to the first RF antenna **16** via the second traditional RF switch **28** and the first traditional antenna matching circuitry **20** based on the first traditional upstream transmit signal TUT1.

When the traditional communications circuitry **10** is receiving RF signals via the first RF antenna **16**, the first traditional RF switch **26** is in the ON state and the second traditional RF switch **28** is in the OFF state. As such, the first traditional antenna matching circuitry **20** is isolated from the first traditional RF transmit circuitry **24** and the first traditional antenna matching circuitry **20** is electrically coupled to the first traditional RF receive circuitry **22**. In this regard, the first traditional antenna matching circuitry **20** receives the RF signals from the first RF antenna **16** and forwards the RF signals via the first traditional RF switch **26** to the first traditional RF receive circuitry **22**. The first traditional RF switch **26** provides a traditional receive signal TRX to the first traditional RF receive circuitry **22**, which provides a first traditional downstream receive signal TDR1 to the traditional RF system control circuitry **12** based on the traditional receive signal TRX.

Since the traditional communications circuitry **10** illustrated in FIG. 1 is a half-duplex system, during operation, the first traditional RF switch **26** and the second traditional RF switch **28** are not simultaneously in the ON state. Therefore, the first traditional RF receive circuitry **22** and the first traditional RF transmit circuitry **24** are isolated from one another. As such, the first traditional RF receive circuitry **22** and the first traditional RF transmit circuitry **24** are prevented from interfering with one another.

FIG. 2 shows the traditional communications circuitry **10** according to the prior art. The traditional communications circuitry **10** illustrated in FIG. 2 is similar to the traditional communications circuitry **10** illustrated in FIG. 1, except in the traditional communications circuitry **10** illustrated in FIG. 2, the traditional RF front-end control circuitry **18**, the first traditional RF switch **26**, and the second traditional RF switch **28** are omitted, and the traditional RF front-end circuitry **14** further includes a first traditional RF duplexer **30**. The first traditional RF duplexer **30** is coupled between the first traditional antenna matching circuitry **20** and the first traditional RF receive circuitry **22**, and is further coupled between the first traditional antenna matching circuitry **20** and the first traditional RF transmit circuitry **24**.

The traditional communications circuitry **10** illustrated in FIG. 2 may be used as a TDD system or a simplex system. However, the traditional communications circuitry **10** illustrated in FIG. 2 may also be used as a frequency-division duplex (FDD) system, which is capable of transmitting and receiving RF signals simultaneously. Such a system may also be called a full-duplex system.

When the traditional communications circuitry **10** is transmitting RF signals via the first RF antenna **16**, the traditional RF system control circuitry **12** provides the first traditional upstream transmit signal TUT1 to the first traditional RF transmit circuitry **24**, which provides the traditional transmit signal TTX to the first RF antenna **16** via first traditional RF duplexer **30** based on the first traditional upstream transmit signal TUT1.

When the traditional communications circuitry **10** is receiving RF signals via the first RF antenna **16**, the first traditional antenna matching circuitry **20** receives the RF signals from the first RF antenna **16** and forwards the RF signals via the first traditional RF duplexer **30** to the first traditional RF receive circuitry **22**. As such, the first traditional RF duplexer **30** provides the traditional receive signal TRX to the first traditional RF receive circuitry **22**, which provides the first traditional downstream receive signal TDR1 to the traditional RF system control circuitry **12** based on the traditional receive signal TRX.

The first traditional RF duplexer **30** provides filtering, such that the first traditional RF receive circuitry **22** and the first traditional RF transmit circuitry **24** are substantially isolated from one another. As such, the first traditional RF receive circuitry **22** and the first traditional RF transmit circuitry **24** are prevented from interfering with one another. Traditional FDD systems using duplexers with high rejection ratios have a fixed frequency transfer. Covering multiple communications bands requires multiple duplexers and switches to route RF signals through appropriate signal paths.

FIG. **3** shows the traditional communications circuitry **10** according to the prior art. The traditional communications circuitry **10** illustrated in FIG. **3** is a carrier aggregation (CA) based system, which is capable of transmitting or receiving multiple simultaneous transmit signals or multiple simultaneous receive signals, respectively, or both. Each of the simultaneous transmit signals is in a frequency band that is different from each frequency band of a balance of the simultaneous transmit signals. Similarly, each of the simultaneous receive signals is in a frequency band that is different from each frequency band of a balance of the simultaneous receive signals. The traditional communications circuitry **10** may operate as a simplex system, a half-duplex system, or a full-duplex system.

The traditional communications circuitry **10** includes the traditional RF system control circuitry **12**, the traditional RF front-end circuitry **14**, the first RF antenna **16**, and a second RF antenna **32**. The traditional RF front-end circuitry **14** includes the first traditional antenna matching circuitry **20**, the first traditional RF receive circuitry **22**, the first traditional RF transmit circuitry **24**, the first traditional RF duplexer **30**, first traditional antenna switching circuitry **34**, a second traditional RF duplexer **36**, a third traditional RF duplexer **38**, second traditional antenna matching circuitry **40**, second traditional antenna switching circuitry **42**, a fourth traditional RF duplexer **44**, a fifth traditional RF duplexer **46**, a sixth traditional RF duplexer **48**, second traditional RF receive circuitry **50**, and second traditional RF transmit circuitry **52**. Traditional CA systems use fixed frequency filters and diplexers, triplexers, or both to combine signal paths, which increases complexity. Alternatively, additional switch paths may be used, but may degrade performance.

The first traditional antenna matching circuitry **20** is coupled between the first RF antenna **16** and the first traditional antenna switching circuitry **34**. The second traditional antenna matching circuitry **40** is coupled between the second RF antenna **32** and the second traditional antenna switching circuitry **42**. The first traditional RF duplexer **30** is coupled between the first traditional antenna switching circuitry **34** and the first traditional RF receive circuitry **22**, and is further coupled between the first traditional antenna switching circuitry **34** and the first traditional RF transmit circuitry **24**. The second traditional RF duplexer **36** is coupled between the first traditional antenna switching circuitry **34** and the first traditional RF receive circuitry **22**, and is further coupled between the first traditional antenna switching circuitry **34** and the first

traditional RF transmit circuitry **24**. The third traditional RF duplexer **38** is coupled between the first traditional antenna switching circuitry **34** and the first traditional RF receive circuitry **22**, and is further coupled between the first traditional antenna switching circuitry **34** and the first traditional RF transmit circuitry **24**.

The fourth traditional RF duplexer **44** is coupled between the second traditional antenna switching circuitry **42** and the second traditional RF receive circuitry **50**, and is further coupled between the second traditional antenna switching circuitry **42** and the second traditional RF transmit circuitry **52**. The fifth traditional RF duplexer **46** is coupled between the second traditional antenna switching circuitry **42** and the second traditional RF receive circuitry **50**, and is further coupled between the second traditional antenna switching circuitry **42** and the second traditional RF transmit circuitry **52**. The sixth traditional RF duplexer **48** is coupled between the second traditional antenna switching circuitry **42** and the second traditional RF receive circuitry **50**, and is further coupled between the second traditional antenna switching circuitry **42** and the second traditional RF transmit circuitry **52**.

The first traditional RF duplexer **30** is associated with a first aggregated receive band, a first aggregated transmit band, or both. The second traditional RF duplexer **36** is associated with a second aggregated receive band, a second aggregated transmit band, or both. The third traditional RF duplexer **38** is associated with a third aggregated receive band, a third aggregated transmit band, or both. The fourth traditional RF duplexer **44** is associated with a fourth aggregated receive band, a fourth aggregated transmit band, or both. The fifth traditional RF duplexer **46** is associated with a fifth aggregated receive band, a fifth aggregated transmit band, or both. The sixth traditional RF duplexer **48** is associated with a sixth aggregated receive band, a sixth aggregated transmit band, or both.

The first traditional antenna switching circuitry **34** couples a selected one of the first traditional RF duplexer **30**, the second traditional RF duplexer **36**, and the third traditional RF duplexer **38** to the first traditional antenna matching circuitry **20**. Therefore, the first RF antenna **16** is associated with a selected one of the first aggregated receive band, the second aggregated receive band, and the third aggregated receive band; with a selected one of the first aggregated transmit band, the second aggregated transmit band, and the third aggregated transmit band; or both.

Similarly, the second traditional antenna switching circuitry **42** couples a selected one of the fourth traditional RF duplexer **44**, the fifth traditional RF duplexer **46**, and the sixth traditional RF duplexer **48** to the second traditional antenna matching circuitry **40**. Therefore, the second RF antenna **32** is associated with a selected one of the fourth aggregated receive band, the fifth aggregated receive band, and the sixth aggregated receive band; with a selected one of the fourth aggregated transmit band, the fifth aggregated transmit band, and the sixth aggregated transmit band; or both.

During transmit CA, the traditional RF system control circuitry **12** provides the first traditional upstream transmit signal TUT1 to the first traditional RF transmit circuitry **24**, which forwards the first traditional upstream transmit signal TUT1 to the first RF antenna **16** for transmission via the selected one of the first traditional RF duplexer **30**, the second traditional RF duplexer **36**, and the third traditional RF duplexer **38**; via the first traditional antenna switching circuitry **34**; and via the first traditional antenna matching circuitry **20**.

Additionally, during transmit CA, the traditional RF system control circuitry **12** provides a second traditional upstream transmit signal TUT2 to the second traditional RF transmit circuitry **52**, which forwards the second traditional upstream transmit signal TUT2 to the second RF antenna **32** for transmission via the selected one of the fourth traditional RF duplexer **44**, the fifth traditional RF duplexer **46**, and the sixth traditional RF duplexer **48**; via the second traditional antenna switching circuitry **42**; and via the second traditional antenna matching circuitry **40**.

During receive CA, the first RF antenna **16** forwards a received RF signal to the first traditional RF receive circuitry **22** via the first traditional antenna matching circuitry **20**, the first traditional antenna switching circuitry **34**, and the selected one of the first traditional RF duplexer **30**, the second traditional RF duplexer **36**, and the third traditional RF duplexer **38**. The first traditional RF receive circuitry **22** provides the first traditional downstream receive signal TDR1 to the traditional RF system control circuitry **12** based on the received RF signal.

Additionally, during receive CA, the second RF antenna **32** forwards a received RF signal to the second traditional RF receive circuitry **50** via the second traditional antenna matching circuitry **40**, the second traditional antenna switching circuitry **42**, and the selected one of the fourth traditional RF duplexer **44**, the fifth traditional RF duplexer **46**, and the sixth traditional RF duplexer **48**. The second traditional RF receive circuitry **50** provides a second traditional downstream receive signal TDR2 to the traditional RF system control circuitry **12** based on the received RF signal.

Since only the selected one of the first traditional RF duplexer **30**, the second traditional RF duplexer **36**, and the third traditional RF duplexer **38** is coupled to the first traditional antenna matching circuitry **20**; the first traditional antenna switching circuitry **34** isolates each of the first traditional RF duplexer **30**, the second traditional RF duplexer **36**, and the third traditional RF duplexer **38** from one another; and prevents each of the first traditional RF duplexer **30**, the second traditional RF duplexer **36**, and the third traditional RF duplexer **38** from interfering with one another.

Similarly, since only the selected one of the fourth traditional RF duplexer **44**, the fifth traditional RF duplexer **46**, and the sixth traditional RF duplexer **48** is coupled to the second traditional antenna matching circuitry **40**; the second traditional antenna matching circuitry **40** isolates each of the fourth traditional RF duplexer **44**, the fifth traditional RF duplexer **46**, and the sixth traditional RF duplexer **48** from one another; and prevents each of the fourth traditional RF duplexer **44**, the fifth traditional RF duplexer **46**, and the sixth traditional RF duplexer **48** from interfering with one another.

FIG. **4** shows RF communications circuitry **54** according to one embodiment of the RF communications circuitry **54**. The RF communications circuitry **54** includes RF system control circuitry **56**, RF front-end circuitry **58**, and the first RF antenna **16**. The RF front-end circuitry **58** includes a first RF filter structure **60**, RF receive circuitry **62**, and RF transmit circuitry **64**. The first RF filter structure **60** includes a first tunable RF filter path **66** and a second tunable RF filter path **68**. Additionally, the first RF filter structure **60** has a first connection node **70**, a second connection node **72**, and a first common connection node **74**. In one embodiment of the RF system control circuitry **56**, the RF system control circuitry **56** is an RF transceiver. In one embodiment of the first tunable RF filter path **66**, the first tunable RF filter path **66** includes a pair of weakly coupled resonators R(**1,1**), R(**1,2**) (FIG. **22**). As such, in one embodiment of the first RF filter structure **60**,

the RF filter structure **60** includes the pair of weakly coupled resonators R(**1,1**), R(**1,2**) (FIG. **21**).

In alternate embodiments of the first RF filter structure **60**, any or all of the first connection node **70**, the second connection node **72**, and the first common connection node **74** are external to the first RF filter structure **60**. In one embodiment of the first tunable RF filter path **66**, the first tunable RF filter path **66** includes a first pair (not shown) of weakly coupled resonators. In one embodiment of the second tunable RF filter path **68**, the second tunable RF filter path **68** includes a second pair (not shown) of weakly coupled resonators.

In one embodiment of the first RF filter structure **60**, the first tunable RF filter path **66** is directly coupled between the first common connection node **74** and the first connection node **70**, the second tunable RF filter path **68** is directly coupled between the second connection node **72** and the first common connection node **74**, and the first RF antenna **16** is directly coupled to the first common connection node **74**. In another embodiment of the RF communications circuitry **54**, the first RF antenna **16** is omitted. Additionally, the RF receive circuitry **62** is coupled between the first connection node **70** and the RF system control circuitry **56**, and the RF transmit circuitry **64** is coupled between the second connection node **72** and the RF system control circuitry **56**.

In one embodiment of the RF communications circuitry **54**, the first tunable RF filter path **66** is a first RF receive filter, such that the first RF antenna **16** forwards a received RF signal via the first common connection node **74** to provide a first upstream RF receive signal RU1 to the first tunable RF filter path **66**, which receives and filters the first upstream RF receive signal RU1 to provide a first filtered RF receive signal RF1 to the RF receive circuitry **62**. The RF receive circuitry **62** may include down-conversion circuitry, amplification circuitry, power supply circuitry, filtering circuitry, switching circuitry, combining circuitry, splitting circuitry, dividing circuitry, clocking circuitry, the like, or any combination thereof. The RF receive circuitry **62** processes the first filtered RF receive signal RF1 to provide a first receive signal RX1 to the RF system control circuitry **56**.

In one embodiment of the RF communications circuitry **54**, the second tunable RF filter path **68** is a first RF transmit filter, such that the RF system control circuitry **56** provides a first transmit signal TX1 to the RF transmit circuitry **64**, which processes the first transmit signal TX1 to provide a first upstream RF transmit signal TU1 to the second tunable RF filter path **68**. The RF transmit circuitry **64** may include up-conversion circuitry, amplification circuitry, power supply circuitry, filtering circuitry, switching circuitry, combining circuitry, splitting circuitry, dividing circuitry, clocking circuitry, the like, or any combination thereof. The second tunable RF filter path **68** receives and filters the first upstream RF transmit signal TU1 to provide a first filtered RF transmit signal TF1, which is transmitted via the first common connection node **74** by the first RF antenna **16**.

The RF system control circuitry **56** provides a first filter control signal FCS1 to the first tunable RF filter path **66** and provides a second filter control signal FCS2 to the second tunable RF filter path **68**. As such, in one embodiment of the RF communications circuitry **54**, the RF system control circuitry **56** tunes a first filter parameter of the first tunable RF filter path **66** using the first filter control signal FCS1. Additionally, the RF system control circuitry **56** tunes a first filter parameter of the second tunable RF filter path **68** using the second filter control signal FCS2.

In one embodiment of the RF communications circuitry **54**, the first tunable RF filter path **66** and the second tunable RF filter path **68** do not significantly load one another at frequen-

cies of interest. As such, by directly coupling the first tunable RF filter path **66** and the second tunable RF filter path **68** to the first common connection node **74**; front-end RF switching elements may be avoided, thereby reducing cost, size, and non-linearity; and increasing efficiency and flexibility of the RF communications circuitry **54**. Since tunable RF filters can support multiple communications bands using a single signal path, they can simplify front-end architectures by eliminating switching and duplexing components.

In one embodiment of the RF communications circuitry **54**, the RF communications circuitry **54** is used as an FDD communications system, such that the first upstream RF receive signal RU1 and the first filtered RF transmit signal TF1 are full-duplex signals. In an alternate embodiments of the RF communications circuitry **54**, the RF communications circuitry **54** is used as a TDD communications system, such that the first upstream RF receive signal RU1 and the first filtered RF transmit signal TF1 are half-duplex signals. In additional embodiments of the RF communications circuitry **54**, the RF communications circuitry **54** is used as a simplex communications system, such that the first upstream RF receive signal RU1 is a simplex signal and the first filtered RF transmit signal TF1 is not present. In other embodiments of the RF communications circuitry **54**, the RF communications circuitry **54** is used as a simplex communications system, such that the first upstream RF receive signal RU1 is not present and the first filtered RF transmit signal TF1 is a simplex signal.

FIG. **5** is a graph illustrating filtering characteristics of the first tunable RF filter path **66** and the second tunable RF filter path **68** illustrated in FIG. **4** according to one embodiment of the first tunable RF filter path **66** and the second tunable RF filter path **68**. The first tunable RF filter path **66** is a first RF bandpass filter, which functions as the first RF receive filter, and the second tunable RF filter path **68** is a second RF bandpass filter, which functions as the first RF transmit filter. A bandwidth **76** of the first RF bandpass filter, a center frequency **78** of the first RF bandpass filter, a bandwidth **80** of the second RF bandpass filter, a center frequency **82** of the second RF bandpass filter, a frequency **84** of the first upstream RF receive signal RU1 (FIG. **4**), and a frequency **86** of the first filtered RF transmit signal TF1 (FIG. **4**) are shown. Operation of the first RF bandpass filter and the second RF bandpass filter is such that the first RF bandpass filter and the second RF bandpass filter do not significantly interfere with one another. In this regard, the bandwidth **76** of the first RF bandpass filter does not overlap the bandwidth **80** of the second RF bandpass filter.

In one embodiment of the first RF receive filter and the first RF transmit filter, the first RF receive filter and the first RF transmit filter in combination function as an RF duplexer. As such, a duplex frequency **88** of the RF duplexer is about equal to a difference between the frequency **84** of the first upstream RF receive signal RU1 (FIG. **4**) and the frequency **86** of the first filtered RF transmit signal TF1 (FIG. **4**).

In one embodiment of the first tunable RF filter path **66**, the first filter parameter of the first tunable RF filter path **66** is tunable based on the first filter control signal FCS1. In an alternate embodiment of the first tunable RF filter path **66**, both the first filter parameter of the first tunable RF filter path **66** and a second filter parameter of the first tunable RF filter path **66** are tunable based on the first filter control signal FCS1. Similarly, in one embodiment of the second tunable RF filter path **68**, the first filter parameter of the second tunable RF filter path **68** is tunable based on the second filter control signal FCS2. In an alternate embodiment of the second tunable RF filter path **68**, both the first filter parameter of

the second tunable RF filter path **68** and a second filter parameter of the second tunable RF filter path **68** are tunable based on the second filter control signal FCS2.

The first filter parameter of the first tunable RF filter path **66** is the center frequency **78** of the first RF bandpass filter. The second filter parameter of the first tunable RF filter path **66** is the bandwidth **76** of the first RF bandpass filter. The first filter parameter of the second tunable RF filter path **68** is the center frequency **82** of the second RF bandpass filter. The second filter parameter of the second tunable RF filter path **68** is the bandwidth **80** of the second RF bandpass filter.

FIGS. **6A** and **6B** are graphs illustrating filtering characteristics of the first tunable RF filter path **66** and the second tunable RF filter path **68**, respectively, illustrated in FIG. **4** according to an alternate embodiment of the first tunable RF filter path **66** and the second tunable RF filter path **68**, respectively. The first tunable RF filter path **66** is an RF lowpass filter and the second tunable RF filter path **68** is an RF highpass filter. FIG. **6A** shows a frequency response curve **90** of the RF lowpass filter and FIG. **6B** shows a frequency response curve **92** of the RF highpass filter. Additionally FIG. **6A** shows a break frequency **94** of the RF lowpass filter and FIG. **6B** shows a break frequency **96** of the RF highpass filter. Both FIGS. **6A** and **6B** show the frequency **84** of the first upstream RF receive signal RU1 (FIG. **4**), the frequency **86** of the first filtered RF transmit signal TF1 (FIG. **4**), and the duplex frequency **88** of the RF duplexer for clarification. However, the RF lowpass filter and the RF highpass filter in combination function as an RF diplexer. The first filter parameter of the first tunable RF filter path **66** is the break frequency **94** of the RF lowpass filter. In one embodiment of the RF lowpass filter, the RF lowpass filter has bandpass filter characteristics. The first filter parameter of the second tunable RF filter path **68** is the break frequency **96** of the RF highpass filter. In one embodiment of the RF highpass filter, the RF highpass filter has bandpass filter characteristics. In one embodiment of the RF diplexer, the break frequency **96** of the RF highpass filter is about equal to the break frequency **94** of the RF lowpass filter.

FIG. **7** shows the RF communications circuitry **54** according to one embodiment of the RF communications circuitry **54**. The RF communications circuitry **54** illustrated in FIG. **7** is similar to the RF communications circuitry **54** illustrated in FIG. **4**, except in the RF front-end circuitry **58** illustrated in FIG. **7**, the RF transmit circuitry **64** (FIG. **4**) is omitted and the RF front-end circuitry **58** further includes RF front-end control circuitry **98**.

The RF system control circuitry **56** provides a front-end control signal FEC to the RF front-end control circuitry **98**. The RF front-end control circuitry **98** provides the first filter control signal FCS1 and the second filter control signal FCS2 based on the front-end control signal FEC. In the RF communications circuitry **54** illustrated in FIG. **4**, the RF system control circuitry **56** provides the first filter control signal FCS1 and the second filter control signal FCS2 directly. In general, the RF communications circuitry **54** includes control circuitry, which may be either the RF system control circuitry **56** or the RF front-end control circuitry **98**, that provides the first filter control signal FCS1 and the second filter control signal FCS2. As such, in one embodiment of the RF communications circuitry **54**, the control circuitry tunes a first filter parameter of the first tunable RF filter path **66** using the first filter control signal FCS1. Additionally, the control circuitry tunes a first filter parameter of the second tunable RF filter path **68** using the second filter control signal FCS2. In an additional embodiment of the RF communications circuitry **54**, the control circuitry further tunes a second filter parameter

of the first tunable RF filter path **66** using the first filter control signal FCS1; and the control circuitry further tunes a second filter parameter of the second tunable RF filter path **68** using the second filter control signal FCS2.

In alternate embodiments of the first RF filter structure **60**, any or all of the first connection node **70**, the second connection node **72**, and the first common connection node **74** are external to the first RF filter structure **60**. In one embodiment of the first tunable RF filter path **66**, the first tunable RF filter path **66** includes a first pair (not shown) of weakly coupled resonators. In one embodiment of the second tunable RF filter path **68**, the second tunable RF filter path **68** includes a second pair (not shown) of weakly coupled resonators.

In one embodiment of the first RF filter structure **60**, the first tunable RF filter path **66** is directly coupled between the first common connection node **74** and the first connection node **70**, the second tunable RF filter path **68** is directly coupled between the second connection node **72** and the first common connection node **74**, and the first RF antenna **16** is directly coupled to the first common connection node **74**. In another embodiment of the RF communications circuitry **54**, the first RF antenna **16** is omitted. Additionally, the RF receive circuitry **62** is coupled between the first connection node **70** and the RF system control circuitry **56**, and the RF receive circuitry **62** is further coupled between the second connection node **72** and the RF system control circuitry **56**.

In one embodiment of the RF communications circuitry **54**, the first tunable RF filter path **66** is a first RF receive filter, such that the first RF antenna **16** forwards a first received RF signal via the first common connection node **74** to provide a first upstream RF receive signal RU1 to the first tunable RF filter path **66**, which receives and filters the first upstream RF receive signal RU1 to provide a first filtered RF receive signal RF1 to the RF receive circuitry **62**. Additionally, the second tunable RF filter path **68** is a second RF receive filter, such that the first RF antenna **16** forwards a second received RF signal via the first common connection node **74** to provide a second upstream RF receive signal RU2 to the second tunable RF filter path **68**, which receives and filters the second upstream RF receive signal RU2 to provide a second filtered RF receive signal RF2 to the RF receive circuitry **62**.

The RF receive circuitry **62** may include down-conversion circuitry, amplification circuitry, power supply circuitry, filtering circuitry, switching circuitry, combining circuitry, splitting circuitry, dividing circuitry, clocking circuitry, the like, or any combination thereof. The RF receive circuitry **62** processes the first filtered RF receive signal RF1 to provide a first receive signal RX1 to the RF system control circuitry **56**. Additionally, the RF receive circuitry **62** processes the second filtered RF receive signal RF2 to provide a second receive signal RX2 to the RF system control circuitry **56**.

In one embodiment of the RF communications circuitry **54**, the first tunable RF filter path **66** and the second tunable RF filter path **68** do not significantly load one another at frequencies of interest. As such, by directly coupling the first tunable RF filter path **66** and the second tunable RF filter path **68** to the first common connection node **74**; front-end RF switching elements may be avoided, thereby reducing cost, size, and non-linearity; and increasing efficiency and flexibility of the RF communications circuitry **54**.

In this regard, in one embodiment of the first tunable RF filter path **66** and the second tunable RF filter path **68**, each of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a bandpass filter having a unique center frequency. As such, the first filter parameter of each of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a unique center frequency.

In an alternate embodiment of the first tunable RF filter path **66** and the second tunable RF filter path **68**, one of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a lowpass filter, and another of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a highpass filter. As such, the first filter parameter of each of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a break frequency.

In an additional embodiment of the first tunable RF filter path **66** and the second tunable RF filter path **68**, one of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a lowpass filter, and another of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a bandpass filter. As such, the first filter parameter of one of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a center frequency, and the first filter parameter of another of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a break frequency.

In an additional embodiment of the first tunable RF filter path **66** and the second tunable RF filter path **68**, one of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a highpass filter, and another of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a bandpass filter. As such, the first filter parameter of one of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a center frequency, and the first filter parameter of another of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a break frequency.

In one embodiment of the RF communications circuitry **54**, the RF communications circuitry **54** is a receive only CA system, such that the first tunable RF filter path **66**, which is the first RF receive filter, and the second tunable RF filter path **68**, which is the second RF receive filter, simultaneously receive and filter the first upstream RF receive signal RU1 and the second upstream RF receive signal RU2, respectively, via the first common connection node **74**. As such, the first RF filter structure **60** functions as a de-multiplexer. In this regard, each of the first upstream RF receive signal RU1 and the second upstream RF receive signal RU2 has a unique carrier frequency. Using receive CA may increase an effective receive bandwidth of the RF communications circuitry **54**.

In another embodiment of the RF communications circuitry **54**, the RF communications circuitry **54** is a receive only communications system, such that the first tunable RF filter path **66**, which is the first RF receive filter, and the second tunable RF filter path **68**, which is the second RF receive filter, do not simultaneously receive and filter the first upstream RF receive signal RU1 and the second upstream RF receive signal RU2, respectively. As such, the first upstream RF receive signal RU1 and the second upstream RF receive signal RU2 are nonsimultaneous signals. Each of the first upstream RF receive signal RU1 and the second upstream RF receive signal RU2 may be associated with a unique RF communications band.

FIG. **8** shows the RF communications circuitry **54** according to an alternate embodiment of the RF communications circuitry **54**. The RF communications circuitry **54** illustrated in FIG. **8** is similar to the RF communications circuitry **54** illustrated in FIG. **7**, except in the RF front-end circuitry **58** illustrated in FIG. **8**, the RF receive circuitry **62** is omitted and the RF transmit circuitry **64** is included.

The RF system control circuitry **56** provides the front-end control signal FEC to the RF front-end control circuitry **98**. The RF front-end control circuitry **98** provides the first filter control signal FCS1 and the second filter control signal FCS2 based on the front-end control signal FEC. In the RF communications circuitry **54** illustrated in FIG. **4**, the RF system

control circuitry **56** provides the first filter control signal FCS**1** and the second filter control signal FCS**2** directly. In general, the RF communications circuitry **54** includes control circuitry, which may be either the RF system control circuitry **56** or the RF front-end control circuitry **98**, that provides the first filter control signal FCS**1** and the second filter control signal FCS**2**. As such, in one embodiment of the RF communications circuitry **54**, the control circuitry tunes a first filter parameter of the first tunable RF filter path **66** using the first filter control signal FCS**1**. Additionally, the control circuitry tunes a first filter parameter of the second tunable RF filter path **68** using the second filter control signal FCS**2**. In an additional embodiment of the RF communications circuitry **54**, the control circuitry further tunes a second filter parameter of the first tunable RF filter path **66** using the first filter control signal FCS**1**; and the control circuitry further tunes a second filter parameter of the second tunable RF filter path **68** using the second filter control signal FCS**2**.

In alternate embodiments of the first RF filter structure **60**, any or all of the first connection node **70**, the second connection node **72**, and the first common connection node **74** are external to the first RF filter structure **60**. In one embodiment of the first tunable RF filter path **66**, the first tunable RF filter path **66** includes a first pair (not shown) of weakly coupled resonators. In one embodiment of the second tunable RF filter path **68**, the second tunable RF filter path **68** includes a second pair (not shown) of weakly coupled resonators.

In one embodiment of the first RF filter structure **60**, the first tunable RF filter path **66** is directly coupled between the first common connection node **74** and the first connection node **70**, the second tunable RF filter path **68** is directly coupled between the second connection node **72** and the first common connection node **74**, and the first RF antenna **16** is directly coupled to the first common connection node **74**. In another embodiment of the RF communications circuitry **54**, the first RF antenna **16** is omitted. Additionally, the RF transmit circuitry **64** is coupled between the first connection node **70** and the RF system control circuitry **56**, and the RF transmit circuitry **64** is further coupled between the second connection node **72** and the RF system control circuitry **56**.

In one embodiment of the RF communications circuitry **54**, the first tunable RF filter path **66** is a first RF transmit filter, such that the RF system control circuitry **56** provides the first transmit signal TX**1** to the RF transmit circuitry **64**, which processes the first transmit signal TX**1** to provide a first upstream RF transmit signal TU**1** to the first tunable RF filter path **66**. Similarly, the second tunable RF filter path **68** is a second RF transmit filter, such that the RF system control circuitry **56** provides a second transmit signal TX**2** to the RF transmit circuitry **64**, which processes the second transmit signal TX**2** to provide a second upstream RF transmit signal TU**2** to the second tunable RF filter path **68**.

The RF transmit circuitry **64** may include up-conversion circuitry, amplification circuitry, power supply circuitry, filtering circuitry, switching circuitry, combining circuitry, splitting circuitry, dividing circuitry, clocking circuitry, the like, or any combination thereof. The first tunable RF filter path **66** receives and filters the first upstream RF transmit signal TU**1** to provide the first filtered RF transmit signal TF**1**, which is transmitted via the first common connection node **74** by the first RF antenna **16**. Similarly, the second tunable RF filter path **68** receives and filters the second upstream RF transmit signal TU**2** to provide a second filtered RF transmit signal TF**2**, which is transmitted via the first common connection node **74** by the first RF antenna **16**.

In one embodiment of the RF communications circuitry **54**, the first tunable RF filter path **66** and the second tunable RF

filter path **68** do not significantly load one another at frequencies of interest. As such, by directly coupling the first tunable RF filter path **66** and the second tunable RF filter path **68** to the first common connection node **74**; front-end RF switching elements may be avoided, thereby reducing cost, size, and non-linearity; and increasing efficiency and flexibility of the RF communications circuitry **54**.

In this regard, in one embodiment of the first tunable RF filter path **66** and the second tunable RF filter path **68**, each of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a bandpass filter having a unique center frequency. As such, the first filter parameter of each of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a unique center frequency.

In an alternate embodiment of the first tunable RF filter path **66** and the second tunable RF filter path **68**, one of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a lowpass filter, and another of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a highpass filter. As such, the first filter parameter of each of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a break frequency.

In an additional embodiment of the first tunable RF filter path **66** and the second tunable RF filter path **68**, one of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a lowpass filter, and another of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a bandpass filter. As such, the first filter parameter of one of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a center frequency, and the first filter parameter of another of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a break frequency.

In an additional embodiment of the first tunable RF filter path **66** and the second tunable RF filter path **68**, one of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a highpass filter, and another of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a bandpass filter. As such, the first filter parameter of one of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a center frequency, and the first filter parameter of another of the first tunable RF filter path **66** and the second tunable RF filter path **68** is a break frequency.

In one embodiment of the RF communications circuitry **54**, the RF communications circuitry **54** is a transmit only CA system, such that the first tunable RF filter path **66**, which is the first RF transmit filter, and the second tunable RF filter path **68**, which is the second RF transmit filter, simultaneously receive and filter the first upstream RF transmit signal TU**1** and the second upstream RF transmit signal TU**2**, respectively, to simultaneously provide the first filtered RF transmit signal TF**1** and the second filtered RF transmit signal TF**2**, respectively, via the first common connection node **74**. As such, the first RF filter structure **60** functions as a multiplexer. In this regard, each of the first filtered RF transmit signal TF**1** and the second filtered RF transmit signal TF**2** has a unique carrier frequency. Using transmit CA may increase an effective transmit bandwidth of the RF communications circuitry **54**.

In another embodiment of the RF communications circuitry **54**, the RF communications circuitry **54** is a transmit only communications system, such that the first tunable RF filter path **66**, which is the first RF transmit filter, and the second tunable RF filter path **68**, which is the second RF transmit filter, do not simultaneously receive and filter the first upstream RF transmit signal TU**1** and the second upstream RF transmit signal TU**2**, respectively. As such, the first filtered RF transmit signal TF**1** and the second filtered RF

transmit signal TF2 are nonsimultaneous signals. Each of the first filtered RF transmit signal TF1 and the second filtered RF transmit signal TF2 may be associated with a unique RF communications band.

FIGS. 9A and 9B are graphs illustrating filtering characteristics of the first tunable RF filter path 66 and the second tunable RF filter path 68, respectively, illustrated in FIG. 8 according to an additional embodiment of the first tunable RF filter path 66 and the second tunable RF filter path 68, respectively. FIG. 9A shows a frequency response curve 100 of the first tunable RF filter path 66 and FIG. 9B shows a frequency response curve 102 of the second tunable RF filter path 68. The first tunable RF filter path 66 and the second tunable RF filter path 68 are both bandpass filters having the frequency response curves 100, 102 illustrated in FIGS. 9A and 9B, respectively. In this regard, the first tunable RF filter path 66 and the second tunable RF filter path 68 can be directly coupled to one another via the first common connection node 74 (FIG. 8) without interfering with one another.

FIGS. 10A and 10B are graphs illustrating filtering characteristics of the first traditional RF duplexer 30 and the second traditional RF duplexer 36, respectively, illustrated in FIG. 3 according to the prior art. FIG. 10A shows a frequency response curve 104 of the first traditional RF duplexer 30 and FIG. 10B shows a frequency response curve 106 of the second traditional RF duplexer 36. There is interference 108 between the frequency response curve 104 of the first traditional RF duplexer 30 and the frequency response curve 106 of the second traditional RF duplexer 36 as shown in FIGS. 10A and 10B. In this regard, the first traditional RF duplexer 30 and the second traditional RF duplexer 36 cannot be directly coupled to one another without interfering with one another. To avoid interference between different filters, traditional systems use RF switches to disconnect unused filters.

FIG. 11 shows the RF communications circuitry 54 according to one embodiment of the RF communications circuitry 54. The RF communications circuitry 54 illustrated in FIG. 11 is similar to the RF communications circuitry 54 illustrated in FIG. 8, except in the RF communications circuitry 54 illustrated in FIG. 11, the RF front-end circuitry 58 further includes the RF receive circuitry 62 and the first RF filter structure 60 further includes a third tunable RF filter path 110 and a fourth tunable RF filter path 112. Additionally, the RF front-end circuitry 58 has the first connection node 70, the second connection node 72, the first common connection node 74, a third connection node 114 and a fourth connection node 116, such that all of the first connection node 70, the second connection node 72, the first common connection node 74, the third connection node 114 and the fourth connection node 116 are external to the first RF filter structure 60. In an alternate of the RF front-end circuitry 58, any or all of the first connection node 70, the second connection node 72, the first common connection node 74, a third connection node 114 and a fourth connection node 116 are internal to the first RF filter structure 60.

The RF front-end control circuitry 98 further provides a third filter control signal FCS3 to the third tunable RF filter path 110 and a fourth filter control signal FCS4 to the fourth tunable RF filter path 112 based on the front-end control signal FEC. In one embodiment of the RF communications circuitry 54, the control circuitry tunes a first filter parameter of the third tunable RF filter path 110 using the third filter control signal FCS3. Additionally, the control circuitry tunes a first filter parameter of the fourth tunable RF filter path 112 using the fourth filter control signal FCS4. In an additional embodiment of the RF communications circuitry 54, the control circuitry further tunes a second filter parameter of the

third tunable RF filter path 110 using the third filter control signal FCS3; and the control circuitry further tunes a second filter parameter of the fourth tunable RF filter path 112 using the fourth filter control signal FCS4.

In one embodiment of the third tunable RF filter path 110, the third tunable RF filter path 110 includes a third pair (not shown) of weakly coupled resonators. In one embodiment of the fourth tunable RF filter path 112, the fourth tunable RF filter path 112 includes a fourth pair (not shown) of weakly coupled resonators.

In one embodiment of the third tunable RF filter path 110 and the fourth tunable RF filter path 112, the third tunable RF filter path 110 is directly coupled between the first common connection node 74 and the third connection node 114, and the fourth tunable RF filter path 112 is directly coupled between the fourth connection node 116 and the first common connection node 74. In another embodiment of the RF communications circuitry 54, the first RF antenna 16 is omitted. Additionally, the RF receive circuitry 62 is coupled between the third connection node 114 and the RF system control circuitry 56, and the RF receive circuitry 62 is further coupled between the fourth connection node 116 and the RF system control circuitry 56.

In one embodiment of the RF communications circuitry 54, the third tunable RF filter path 110 is the first RF receive filter, such that the first RF antenna 16 forwards a first received RF signal via the first common connection node 74 to provide the first upstream RF receive signal RU1 to the third tunable RF filter path 110, which receives and filters the first upstream RF receive signal RU1 to provide the first filtered RF receive signal RF1 to the RF receive circuitry 62. Additionally, the fourth tunable RF filter path 112 is a second RF receive filter, such that the first RF antenna 16 forwards a second received RF signal via the first common connection node 74 to provide the second upstream RF receive signal RU2 to the fourth tunable RF filter path 112, which receives and filters the second upstream RF receive signal RU2 to provide the second filtered RF receive signal RF2 to the RF receive circuitry 62.

The RF receive circuitry 62 may include down-conversion circuitry, amplification circuitry, power supply circuitry, filtering circuitry, switching circuitry, combining circuitry, splitting circuitry, dividing circuitry, clocking circuitry, the like, or any combination thereof. The RF receive circuitry 62 processes the first filtered RF receive signal RF1 to provide the first receive signal RX1 to the RF system control circuitry 56. Additionally, the RF receive circuitry 62 processes the second filtered RF receive signal RF2 to provide the second receive signal RX2 to the RF system control circuitry 56.

In one embodiment of the RF communications circuitry 54, the first tunable RF filter path 66, the second tunable RF filter path 68, the third tunable RF filter path 110, and the fourth tunable RF filter path 112 do not significantly load one another at frequencies of interest. As such, by directly coupling the first tunable RF filter path 66, the second tunable RF filter path 68, the third tunable RF filter path 110, and the fourth tunable RF filter path 112 to the first common connection node 74; front-end RF switching elements may be avoided, thereby reducing cost, size, and non-linearity; and increasing efficiency and flexibility of the RF communications circuitry 54.

In this regard, in one embodiment of the third tunable RF filter path 110 and the fourth tunable RF filter path 112, each of the third tunable RF filter path 110 and the fourth tunable RF filter path 112 is a bandpass filter having a unique center frequency. As such, the first filter parameter of each of the third tunable RF filter path 110 and the fourth tunable RF filter path 112 is a unique center frequency.

In an alternate embodiment of the third tunable RF filter path 110 and the fourth tunable RF filter path 112, one of the third tunable RF filter path 110 and the fourth tunable RF filter path 112 is a lowpass filter, and another of the third tunable RF filter path 110 and the fourth tunable RF filter path 112 is a highpass filter. As such, the first filter parameter of each of the third tunable RF filter path 110 and the fourth tunable RF filter path 112 is a break frequency.

In an additional embodiment of the third tunable RF filter path 110 and the fourth tunable RF filter path 112, one of the third tunable RF filter path 110 and the fourth tunable RF filter path 112 is a lowpass filter, and another of the third tunable RF filter path 110 and the fourth tunable RF filter path 112 is a bandpass filter. As such, the first filter parameter of one of the third tunable RF filter path 110 and the fourth tunable RF filter path 112 is a center frequency, and the first filter parameter of another of the third tunable RF filter path 110 and the fourth tunable RF filter path 112 is a break frequency.

In an additional embodiment of the third tunable RF filter path 110 and the fourth tunable RF filter path 112, one of the third tunable RF filter path 110 and the fourth tunable RF filter path 112 is a highpass filter, and another of the third tunable RF filter path 110 and the fourth tunable RF filter path 112 is a bandpass filter. As such, the first filter parameter of one of the third tunable RF filter path 110 and the fourth tunable RF filter path 112 is a center frequency, and the first filter parameter of another of the third tunable RF filter path 110 and the fourth tunable RF filter path 112 is a break frequency.

In one embodiment of the RF communications circuitry 54, the RF communications circuitry 54 is a CA system, such that the third tunable RF filter path 110, which is the first RF receive filter, and the fourth tunable RF filter path 112, which is the second RF receive filter, simultaneously receive and filter the first upstream RF receive signal RU1 and the second upstream RF receive signal RU2, respectively, via the first common connection node 74. As such, the first RF filter structure 60 functions as a de-multiplexer using the third tunable RF filter path 110 and the fourth tunable RF filter path 112. In one embodiment of the first RF filter structure 60, the first RF filter structure 60 further functions as a multiplexer using the first tunable RF filter path 66 and the second tunable RF filter path 68. In this regard, each of the first upstream RF receive signal RU1 and the second upstream RF receive signal RU2 has a unique carrier frequency.

In another embodiment of the RF communications circuitry 54, the RF communications circuitry 54 is a receive communications system, such that the third tunable RF filter path 110, which is the first RF receive filter, and the fourth tunable RF filter path 112, which is the second RF receive filter, do not simultaneously receive and filter the first upstream RF receive signal RU1 and the second upstream RF receive signal RU2, respectively. As such, the first upstream RF receive signal RU1 and the second upstream RF receive signal RU2 are nonsimultaneous signals. Each of the first upstream RF receive signal RU1 and the second upstream RF receive signal RU2 may be associated with a unique RF communications band.

FIG. 12 shows the RF communications circuitry 54 according to an alternate embodiment of the RF communications circuitry 54. The RF communications circuitry 54 illustrated in FIG. 12 is similar to the RF communications circuitry 54 illustrated in FIG. 11, except the RF communications circuitry 54 illustrated in FIG. 12 further includes the second RF antenna 32. Additionally, the RF front-end circuitry 58 further includes a second common connection node 118 and a second RF filter structure 120. The third tunable RF filter path 110 and the fourth tunable RF filter path 112 are included in

the second RF filter structure 120 instead of being included in the first RF filter structure 60. Instead of being coupled to the first common connection node 74, the third tunable RF filter path 110 and the fourth tunable RF filter path 112 are coupled to the second common connection node 118. In one embodiment of the third tunable RF filter path 110 and the fourth tunable RF filter path 112, the third tunable RF filter path 110 and the fourth tunable RF filter path 112 are directly coupled to the second common connection node 118. In one embodiment of the RF communications circuitry 54, the second RF antenna 32 is coupled to the second common connection node 118.

FIG. 13 shows the RF communications circuitry 54 according to an additional embodiment of the RF communications circuitry 54. The RF communications circuitry 54 illustrated in FIG. 13 is similar to the RF communications circuitry 54 illustrated in FIG. 12, except in the RF communications circuitry 54 illustrated in FIG. 13, the RF front-end control circuitry 98 provides a front-end status signal FES to the RF system control circuitry 56. Additionally, the RF front-end control circuitry 98 provides a first calibration control signal CCS1 and up to and including an N^{TH} calibration control signal CCSN to the first RF filter structure 60. The RF front-end control circuitry 98 provides a P^{TH} calibration control signal CCSP and up to and including an X^{TH} calibration control signal CCSX to the second RF filter structure 120. Details of the first RF filter structure 60 and the second RF filter structure 120 are not shown to simplify FIG. 13.

The first RF filter structure 60 provides a first calibration status signal CSS1 and up to and including a Q^{TH} calibration status signal CSSQ to the RF front-end control circuitry 98. The second RF filter structure 120 provides an R^{TH} calibration status signal CSSR and up to and including a Y^{TH} calibration status signal CSSY to the RF front-end control circuitry 98. In an alternate embodiment of the RF front-end circuitry 58, any or all of the N^{TH} calibration control signal CCSN, the Q^{TH} calibration status signal CSSQ, the X^{TH} calibration control signal CCSX, and the Y^{TH} calibration status signal CSSY are omitted.

In one embodiment of the RF front-end circuitry 58, the RF front-end circuitry 58 operates in one of a normal operating mode and a calibration mode. During the calibration mode, the RF front-end control circuitry 98 performs a calibration of the first RF filter structure 60, the second RF filter structure 120, or both. As such, the RF front-end control circuitry 98 provides any or all of the filter control signals FCS1, FCS2, FCS3, FCS4 and any or all of the calibration control signals CCS1, CCSN, CCSP, CCSX needed for calibration. Further, the RF front-end control circuitry 98 receives any or all of the calibration status signals CSS1, CSSQ, CSSR, CSSY needed for calibration.

During the normal operating mode, the RF front-end control circuitry 98 provides any or all of the filter control signals FCS1, FCS2, FCS3, FCS4 and any or all of the calibration control signals CCS1, CCSN, CCSP, CCSX needed for normal operation. Further, the RF front-end control circuitry 98 receives any or all of the calibration status signals CSS1, CSSQ, CSSR, CSSY needed for normal operation. Any or all of the calibration control signals CCS1, CCSN, CCSP, CCSX may be based on the front-end control signal FEC. The front-end status signal FES may be based on any or all of the calibration status signals CSS1, CSSQ, CSSR, CSSY. Further, during the normal operating mode, the RF front-end circuitry 58 processes signals as needed for normal operation. Other embodiments described in the present disclosure may be associated with normal operation.

The RF communications circuitry **54** illustrated in FIG. **13** includes the first RF antenna **16** and the second RF antenna **32**. In general, the RF communications circuitry **54** is a multiple antenna system. A single-input single-output (SISO) antenna system is a system in which RF transmit signals may be transmitted from the first RF antenna **16** and RF receive signals may be received via the second RF antenna **32**. In one embodiment of the RF communications circuitry **54**, the antenna system in the RF communications circuitry **54** is a SISO antenna system, as illustrated in FIG. **13**.

A single-input multiple-output (SIMO) antenna system is a system in which RF transmit signals may be simultaneously transmitted from the first RF antenna **16** and the second RF antenna **32**, and RF receive signals may be received via the second RF antenna **32**. In an alternate embodiment of the RF communications circuitry **54**, the second RF filter structure **120** is coupled to the RF transmit circuitry **64**, such that the antenna system in the RF communications circuitry **54** is a SIMO antenna system.

A multiple-input single-output (MISO) antenna system is a system in which RF transmit signals may be transmitted from the first RF antenna **16**, and RF receive signals may be simultaneously received via the first RF antenna **16** and the second RF antenna **32**. In an additional embodiment of the RF communications circuitry **54**, the first RF filter structure **60** is coupled to the RF receive circuitry **62**, such that the antenna system in the RF communications circuitry **54** is a MISO antenna system.

A multiple-input multiple-output (MIMO) antenna system is a system in which RF transmit signals may be simultaneously transmitted from the first RF antenna **16** and the second RF antenna **32**, and RF receive signals may be simultaneously received via the first RF antenna **16** and the second RF antenna **32**. In another embodiment of the RF communications circuitry **54**, the second RF filter structure **120** is coupled to the RF transmit circuitry **64** and the first RF filter structure **60** is coupled to the RF receive circuitry **62**, such that the antenna system in the RF communications circuitry **54** is a MIMO antenna system.

FIG. **14** shows the RF communications circuitry **54** according to another embodiment of the RF communications circuitry **54**. The RF communications circuitry **54** illustrated in FIG. **14** is similar to the RF communications circuitry **54** illustrated in FIG. **11**, except in the RF communications circuitry **54** illustrated in FIG. **14**, the first RF filter structure **60** further includes a fifth tunable RF filter path **122** and a sixth tunable RF filter path **124**, and the RF front-end circuitry **58** further includes a fifth connection node **126** and a sixth connection node **128**. Additionally, the RF front-end control circuitry **98** shown in FIG. **11** is not shown in FIG. **14** to simplify FIG. **14**.

In one embodiment of the fifth tunable RF filter path **122**, the fifth tunable RF filter path **122** includes a fifth pair (not shown) of weakly coupled resonators. In one embodiment of the sixth tunable RF filter path **124**, the sixth tunable RF filter path **124** includes a sixth pair (not shown) of weakly coupled resonators.

In one embodiment of the fifth tunable RF filter path **122** and the sixth tunable RF filter path **124**, the fifth tunable RF filter path **122** is directly coupled between the first common connection node **74** and the fifth connection node **126**, and the sixth tunable RF filter path **124** is directly coupled between the sixth connection node **128** and the first common connection node **74**. In another embodiment of the RF communications circuitry **54**, the first RF antenna **16** is omitted. Additionally, the RF receive circuitry **62** is further coupled between the sixth connection node **128** and the RF system

control circuitry **56**, and the RF transmit circuitry **64** is further coupled between the fifth connection node **126** and the RF system control circuitry **56**.

In one embodiment of the RF communications circuitry **54**, the sixth tunable RF filter path **124** is a third RF receive filter, such that the first RF antenna **16** forwards a third received RF signal via the first common connection node **74** to provide a third upstream RF receive signal RU**3** to the sixth tunable RF filter path **124**, which receives and filters the third upstream RF receive signal RU**3** to provide a third filtered RF receive signal RF**3** to the RF receive circuitry **62**, which processes the third filtered RF receive signal RF**3** to provide the third receive signal RX**3** to the RF system control circuitry **56**.

In one embodiment of the RF communications circuitry **54**, the fifth tunable RF filter path **122** is a third RF transmit filter, such that the RF system control circuitry **56** provides a third transmit signal TX**3** to the RF transmit circuitry **64**, which processes the third transmit signal TX**3** to provide a third upstream RF transmit signal TU**3** to the fifth tunable RF filter path **122**. The fifth tunable RF filter path **122** receives and filters the third upstream RF transmit signal TU**3** to provide a third filtered RF transmit signal TF**3**, which is transmitted via the first common connection node **74** by the first RF antenna **16**.

In one embodiment of the RF communications circuitry **54**, the first tunable RF filter path **66**, the second tunable RF filter path **68**, the third tunable RF filter path **110**, the fourth tunable RF filter path **112**, the fifth tunable RF filter path **122**, and the sixth tunable RF filter path **124** do not significantly load one another at frequencies of interest. Therefore, antenna switching circuitry **34**, **42** (FIG. **3**) may be avoided. As such, by directly coupling the first tunable RF filter path **66**, the second tunable RF filter path **68**, the third tunable RF filter path **110**, the fourth tunable RF filter path **112**, the fifth tunable RF filter path **122** and the sixth tunable RF filter path **124** to the first common connection node **74**; front-end RF switching elements may be avoided, thereby reducing cost, size, and non-linearity; and increasing efficiency and flexibility of the RF communications circuitry **54**.

In one embodiment of the RF communications circuitry **54**, the RF communications circuitry **54** is an FDD communications system, such that each of the first tunable RF filter path **66**, the second tunable RF filter path **68**, the third tunable RF filter path **110**, the fourth tunable RF filter path **112**, the fifth tunable RF filter path **122**, and the sixth tunable RF filter path **124** is a bandpass filter having a unique center frequency. As such, in one embodiment of the RF system control circuitry **56**, the first filter parameter of each of the first tunable RF filter path **66**, the second tunable RF filter path **68**, the third tunable RF filter path **110**, the fourth tunable RF filter path **112**, the fifth tunable RF filter path **122**, and the sixth tunable RF filter path **124** is a unique center frequency.

FIG. **15** shows the RF communications circuitry **54** according to a further embodiment of the RF communications circuitry **54**. The RF communications circuitry **54** illustrated in FIG. **15** is similar to the RF communications circuitry **54** illustrated in FIG. **4**, except in the RF communications circuitry **54** illustrated in FIG. **15**, the RF front-end circuitry **58** further includes an RF antenna switch **130** and the third connection node **114**. Additionally, the first RF filter structure **60** further includes the third tunable RF filter path **110**. Instead of the first RF antenna **16** being directly coupled to the first common connection node **74**, as illustrated in FIG. **4**, the RF antenna switch **130** is coupled between the first RF antenna **16** and the first common connection node **74**. As such, the first common connection node **74** is coupled to the

first RF antenna **16** via the RF antenna switch **130**. In this regard, the RF communications circuitry **54** is a hybrid RF communications system.

The RF antenna switch **130** has an antenna switch common connection node **132**, an antenna switch first connection node **134**, an antenna switch second connection node **136**, and an antenna switch third connection node **138**. The antenna switch common connection node **132** is coupled to the first RF antenna **16**. In one embodiment of the RF antenna switch **130**, the antenna switch common connection node **132** is directly coupled to the first RF antenna **16**. The antenna switch first connection node **134** is coupled to the first common connection node **74**. In one embodiment of the RF antenna switch **130**, the antenna switch first connection node **134** is directly coupled to the first common connection node **74**. The antenna switch second connection node **136** may be coupled to other circuitry (not shown). The antenna switch third connection node **138** may be coupled to other circuitry (not shown). In another embodiment of the RF antenna switch **130**, the antenna switch third connection node **138** is omitted. In a further embodiment of the RF antenna switch **130**, the RF antenna switch **130** has at least one additional connection node.

The RF system control circuitry **56** provides a switch control signal SCS to the RF antenna switch **130**. As such, the RF system control circuitry **56** selects one of the antenna switch first connection node **134**, the antenna switch second connection node **136**, and the antenna switch third connection node **138** to be coupled to the antenna switch common connection node **132** using the switch control signal SCS.

The third tunable RF filter path **110** is directly coupled between the first common connection node **74** and the third connection node **114**. In one embodiment of the RF communications circuitry **54**, the third tunable RF filter path **110** is a second RF receive filter, such that the first RF antenna **16** forwards a received RF signal via the RF antenna switch **130** and the first common connection node **74** to provide the second upstream RF receive signal RU2 to the third tunable RF filter path **110**, which receives and filters the second upstream RF receive signal RU2 to provide the second filtered RF receive signal RF2 to the RF receive circuitry **62**. The RF receive circuitry **62** processes the second filtered RF receive signal RF2 to provide a second receive signal RX2 to the RF system control circuitry **56**.

The RF system control circuitry **56** further provides the third filter control signal FCS3. As such, in one embodiment of the RF communications circuitry **54**, the RF system control circuitry **56** tunes a first filter parameter of the third tunable RF filter path **110** using the third filter control signal FCS3. In one embodiment of the RF communications circuitry **54**, the RF communications circuitry **54** uses the second tunable RF filter path **68** and the third tunable RF filter path **110** to provide receive CA. In an alternate embodiment of the RF communications circuitry **54**, tunable RF filters allow for sharing a signal path to provide both an FDD signal path and a TDD signal path, thereby lowering front-end complexity.

FIG. **16** shows the RF communications circuitry **54** according to one embodiment of the RF communications circuitry **54**. The RF communications circuitry **54** illustrated in FIG. **16** is similar to the RF communications circuitry **54** illustrated in FIG. **15**, except in the RF communications circuitry **54** illustrated in FIG. **16**, the third tunable RF filter path **110** is omitted. Additionally, in one embodiment of the RF communications circuitry **54**, the RF receive circuitry **62**, the RF transmit circuitry **64**, and the first RF filter structure **60** are all broadband devices. As such, the RF communications cir-

cuitry **54** is broadband circuitry capable of processing RF signals having wide frequency ranges.

FIG. **17** shows the RF communications circuitry **54** according to an alternate embodiment of the RF communications circuitry **54**. The RF communications circuitry **54** illustrated in FIG. **17** is similar to the RF communications circuitry **54** illustrated in FIG. **16**, except in the RF communications circuitry **54** illustrated in FIG. **17**, the RF receive circuitry **62** is omitted and the RF front-end circuitry **58** further includes a first RF front-end circuit **140**, a second RF front-end circuit **142**, and a third RF front-end circuit **144**.

The first RF front-end circuit **140** includes the RF transmit circuitry **64**. The second RF front-end circuit **142** includes the first RF filter structure **60**, the first connection node **70**, the second connection node **72**, and the first common connection node **74**. The third RF front-end circuit **144** includes the RF antenna switch **130**. In one embodiment of the first RF front-end circuit **140**, the first RF front-end circuit **140** is a first RF front-end integrated circuit (IC). In one embodiment of the second RF front-end circuit **142**, the second RF front-end circuit **142** is a second RF front-end IC. In one embodiment of the third RF front-end circuit **144**, the third RF front-end circuit **144** is a third RF front-end IC.

FIG. **18** shows the RF communications circuitry **54** according to an additional embodiment of the RF communications circuitry **54**. The RF communications circuitry **54** illustrated in FIG. **18** is similar to the RF communications circuitry **54** illustrated in FIG. **16**, except in the RF communications circuitry **54** illustrated in FIG. **18**, the RF receive circuitry **62** is omitted and the RF front-end circuitry **58** further includes the first RF front-end circuit **140** and the second RF front-end circuit **142**.

The first RF front-end circuit **140** includes the RF transmit circuitry **64**. The second RF front-end circuit **142** includes the first RF filter structure **60**, the RF antenna switch **130**, the first connection node **70**, the second connection node **72**, and the first common connection node **74**. In one embodiment of the first RF front-end circuit **140**, the first RF front-end circuit **140** is the first RF front-end IC. In one embodiment of the second RF front-end circuit **142**, the second RF front-end circuit **142** is the second RF front-end IC.

FIG. **19** shows the RF communications circuitry **54** according to another embodiment of the RF communications circuitry **54**. The RF communications circuitry **54** illustrated in FIG. **19** is similar to the RF communications circuitry **54** illustrated in FIG. **16**, except in the RF communications circuitry **54** illustrated in FIG. **19**, the RF receive circuitry **62** is omitted and the RF front-end circuitry **58** further includes the first RF front-end circuit **140**.

The first RF front-end circuit **140** includes the RF transmit circuitry **64**, the first RF filter structure **60**, the RF antenna switch **130**, the first connection node **70**, the second connection node **72**, and the first common connection node **74**. In one embodiment of the first RF front-end circuit **140**, the first RF front-end circuit **140** is the first RF front-end IC.

FIG. **20** shows the RF communications circuitry **54** according to a further embodiment of the RF communications circuitry **54**. The RF communications circuitry **54** illustrated in FIG. **20** is a TDD system, which is capable of transmitting and receiving RF signals, but not simultaneously. As such, the RF communications circuitry **54** illustrated in FIG. **20** is similar to the RF communications circuitry **54** illustrated in FIG. **4**, except in the RF communications circuitry **54** illustrated in FIG. **20**, the second tunable RF filter path **68** and the second connection node **72** are omitted, and the RF front-end circuitry **58** further includes an RF transmit/receive switch **146** coupled between the first tunable RF filter path **66** and the RF

receive circuitry **62**, and further coupled between the first tunable RF filter path **66** and the RF transmit circuitry **64**.

Since the RF communications circuitry **54** does not simultaneously transmit and receive RF signals, the first tunable RF filter path **66** provides front-end transmit filtering when the RF communications circuitry **54** is transmitting RF signals and the first tunable RF filter path **66** provides front-end receive filtering when the RF communications circuitry **54** is receiving RF signals. In this regard, the first tunable RF filter path **66** processes half-duplex signals.

The RF transmit/receive switch **146** has a transmit/receive switch common connection node **148**, a transmit/receive switch first connection node **150**, and a transmit/receive switch second connection node **152**. The RF receive circuitry **62** is coupled between the RF system control circuitry **56** and the transmit/receive switch second connection node **152**. The RF transmit circuitry **64** is coupled between the RF system control circuitry **56** and the transmit/receive switch first connection node **150**. The first connection node **70** is coupled to the transmit/receive switch common connection node **148**.

The RF system control circuitry **56** provides a switch control signal SCS to the RF transmit/receive switch **146**. As such, the RF system control circuitry **56** selects either the transmit/receive switch first connection node **150** or the transmit/receive switch second connection node **152** to be coupled to the transmit/receive switch common connection node **148** using the switch control signal SCS. Therefore, when the RF communications circuitry **54** is transmitting RF signals, the RF transmit circuitry **64** is coupled to the first tunable RF filter path **66** and the RF receive circuitry **62** is not coupled to the first tunable RF filter path **66**. Conversely, when the RF communications circuitry **54** is receiving RF signals, the RF receive circuitry **62** is coupled to the first tunable RF filter path **66** and the RF transmit circuitry **64** is not coupled to the first tunable RF filter path **66**.

FIG. **21** illustrates an exemplary embodiment of the first RF filter structure **60**. The first RF filter structure **60** includes a plurality of resonators (referred to generically as elements R and specifically as elements R(i,j), where an integer i indicates a row position and an integer j indicates a column position, where 1≤i≤M, 1≤j≤N and M is any integer greater than 1 and N is any integer greater than to 1. It should be noted that in alternative embodiments the number of resonators R in each row and column may be the same or different). The first tunable RF filter path **66** includes row **1** of weakly coupled resonators R(**1**,**1**), R(**1**,**2**) through (R(**1**,N). All of the weakly coupled resonators R(**1**,**1**), R(**1**,**2**) through (R(**1**,N) are weakly coupled to one another. Furthermore, the first tunable RF filter path **66** is electrically connected between terminal **200** and terminal **202**. In this manner, the first tunable RF filter path **66** is configured to receive RF signals and output filtered RF signals. The second tunable RF filter path **68** includes row M of weakly coupled resonators R(M,**1**), R(M,**2**) through R(M,N). All of the weakly coupled resonators R(M,**1**), R(M, **2**) through R(M,N) are weakly coupled to one another. Furthermore, the second tunable RF filter path **68** is electrically connected between terminal **204** and terminal **206**. In this manner, the second tunable RF filter path **68** is configured to receive RF signals and output filtered RF signals. It should be noted that the first RF filter structure **60** may include any number of tunable RF filter paths, such as, for example, the third tunable RF filter path **110**, the fourth tunable RF filter path **112**, the fifth tunable RF filter path **122**, and the sixth tunable RF filter path **124**, described above with respect to FIGS. **11-14**. Each of the resonators R may be a tunable resonator, which allows for a resonant frequency of each of the resonators R to be varied to along a frequency range. In

some embodiments, not all of the couplings between the resonators R are weak. A hybrid architecture having at least one pair of weakly coupled resonators R and strongly or moderately coupled resonators R is also possible.

Cross-coupling capacitive structures C are electrically connected to and between the resonators R. In this embodiment, each of the cross-coupling capacitive structures C is a variable cross-coupling capacitive structure, such as a varactor or an array of capacitors. To be independent, the magnetic couplings may be negligible. Alternatively, the cross-coupling capacitive structures C may simply be provided by a capacitor with a fixed capacitance. With regard to the exemplary embodiment shown in FIG. **21**, the tunable RF filter paths of the first RF filter structure **60** are independent of one another. As such, the first tunable RF filter path **66** and the second tunable RF filter path **68** are independent of one another and thus do not have cross-coupling capacitive structures C between their resonators. Thus, in this embodiment, the cross-coupling capacitive structures C do not connect any of the weakly coupled resonators R(**1**,**1**), R(**1**,**2**) through (R(**1**,N) to any of the weakly coupled resonators R(M,**1**), R(M,**2**) through (R(M,N). This provides increased isolation between the first tunable RF filter path **66** and the second tunable RF filter path **68**. In general, energy transfer between two weakly coupled resonators R in the first tunable RF filter path **66** and the second tunable RF filter path **68** may be provided by multiple energy transfer components. For example, energy may be transferred between the resonators R only through mutual magnetic coupling, only through mutual electric coupling, or through both mutual electric coupling and mutual magnetic coupling. Ideally, all of the mutual coupling coefficients are provided as designed, but in practice, the mutual coupling coefficients also be the result of parasitics. The inductors of the resonators R may also have magnetic coupling between them. A total coupling between the resonators R is given by the sum of magnetic and electric coupling.

In order to provide the transfer functions of the tunable RF filter paths **66**, **68** with high out-of-band attenuation and a relatively low filter order, the tunable RF filter paths **66**, **68** are configured to adjust notches in the transfer function, which are provided by the resonators R within the tunable RF filter paths **66**, **68**. The notches can be provided using parallel tanks connected in series or in shunt along a signal path of the first tunable RF filter path **66**. To provide the notches, the parallel tanks operate approximately as an open circuit or as short circuits at certain frequencies. The notches can also be provided using multi-signal path cancellation. In this case, the tunable RF filter paths **66**, **68** may be smaller and/or have fewer inductors. To tune the total mutual coupling coefficients between the resonators R towards a desired value, the tunable RF filter paths **66**, **68** are configured to vary variable electric coupling coefficients so that parasitic couplings between the resonators R in the tunable RF filter paths **66**, **68** are absorbed into a desired frequency transfer function.

FIG. **22** illustrates an exemplary embodiment of the first tunable RF filter path **66** in the first RF filter structure **60** shown in FIG. **21**. While the exemplary embodiment shown in FIG. **22** is of the first tunable RF filter path **66**, any of the tunable RF filter paths shown in the first RF filter structure **60** of FIG. **21** may be arranged in accordance with the exemplary embodiment shown in FIG. **22**. The first tunable RF filter path **66** shown in FIG. **22** includes an embodiment of the resonator R(**1**,**1**) and an embodiment of the resonator R(**1**,**2**). The resonator R(**1**,**1**) and the resonator R(**1**,**2**) are weakly coupled to one another. More specifically, the resonator R(**1**,**1**) includes an inductor **208** and a capacitive structure **210**. The resonator

R(1,2) includes an inductor 212, a capacitive structure 214, and a capacitive structure 216.

The resonator R(1,1) and the resonator R(1,2) are a pair of weakly coupled resonators. The resonator R(1,1) and the resonator R(1,2) are weakly coupled by providing the inductor 208 and the inductor 212 such that the inductor 208 and the inductor 212 are weakly magnetically coupled. Although the resonator R(1,1) and the resonator R(1,2) are weakly coupled, the inductor 212 has a maximum lateral width and a displacement between the inductor 208 and the inductor 212 is less than or equal to half the maximum lateral width of the inductor 212. As such, the inductor 208 and the inductor 212 are relatively close to one another. The displacement between the inductor 208 and the inductor 212 may be measured from a geometric centroid of the inductor 208 to a geometric centroid of the inductor 212. The maximum lateral width may be a maximum dimension of the inductor 212 along a plane defined by its largest winding. The weak coupling between the inductor 208 and the inductor 212 is obtained through topological techniques. For example, the inductor 208 and the inductor 212 may be fully or partially aligned, where winding(s) of the inductor 208 and winding(s) of the inductor 212 are configured to provide weak coupling through cancellation. Alternatively or additionally, a plane defining an orientation of the winding(s) of the inductor 208 and a plane defining an orientation of the winding(s) of the inductor 212 may be fully or partially orthogonal to one another. Some of the magnetic couplings between the resonators R can be unidirectional (passive or active). This can significantly improve isolation (e.g., transmit and receive isolation in duplexers).

To maximize the quality (Q) factor of the tunable RF filter paths 66 through 68, most of the total mutual coupling should be realized magnetically, and only fine-tuning is provided electrically. This also helps to reduce common-mode signal transfer in the differential resonators and thus keeps the Q factor high. While the magnetic coupling can be adjusted only statically, with a new layout design, the electric coupling can be tuned on the fly (after fabrication). The filter characteristics (e.g., bias network structure, resonator capacitance) can be adjusted based on given coupling coefficients to maximize filter performance.

To provide a tuning range to tune a transfer function of the first tunable RF filter path 66 and provide a fast roll-off from a low-frequency side to a high-frequency side of the transfer function, the first tunable RF filter path 66 is configured to change a sign of a total mutual coupling coefficient between the resonator R(1,1) and the resonator R(1,2). Accordingly, the first tunable RF filter path 66 includes a cross-coupling capacitive structure C(P1) and a cross-coupling capacitive structure C(N1). The cross-coupling capacitive structure C(P1) and the cross-coupling capacitive structure C(N1) are embodiments of the cross-coupling capacitive structures C described above with regard to FIG. 21. As shown in FIG. 22, the cross-coupling capacitive structure C(P1) is electrically connected between the resonator R(1,1) and the resonator R(1,2) so as to provide a positive coupling coefficient between the resonator R(1,1) and the resonator R(1,2). The cross-coupling capacitive structure C(P1) is a variable cross-coupling capacitive structure configured to vary the positive coupling coefficient provided between the resonator R(1,1) and the resonator R(1,2). The cross-coupling capacitive structure C(N1) is electrically connected between the resonator R(1,1) and the resonator R(1,2) so as to provide a negative coupling coefficient between the resonator R(1,1) and the resonator R(1,2). The cross-coupling capacitive structure C(N1) is a variable cross-coupling capacitive structure con-

figured to vary the negative coupling coefficient provided between the resonator R(1,1) and the resonator R(1,2). The arrangement of the cross-coupling capacitive structure C(P1) and the cross-coupling capacitive structure C(N1) shown in FIG. 22 is a V-bridge structure. In alternative embodiments, some or all of the cross-coupling capacitive structures is fixed (not variable).

In the resonator R(1,1), the inductor 208 and the capacitive structure 210 are electrically connected in parallel. More specifically, the inductor 208 has an end 217 and an end 218, which are disposed opposite to one another. The ends 217, 218 are each electrically connected to the capacitive structure 210, which is grounded. Thus, the resonator R(1,1) is a single-ended resonator. On the other hand, the inductor 212 is electrically connected between the capacitive structure 214 and the capacitive structure 216. More specifically, the inductor 212 has an end 220 and an end 222, which are disposed opposite to one another. The end 220 is electrically connected to the capacitive structure 214 and the end 222 is electrically connected to the capacitive structure 216. Both the capacitive structure 214 and the capacitive structure 216 are grounded. Thus, the resonator R(1,2) is a differential resonator. In an alternative, an inductor with a center tap can be used. The tap can be connected to ground and only a single capacitive structure can be used. In yet another embodiment, both an inductor and a capacitive structure may have a center tap that is grounded. In still another embodiment, neither the inductor nor the capacitive structure may have a grounded center tap.

The inductor 208 is magnetically coupled to the inductor 212 such that an RF signal received at the end 217 of the inductor 208 with a voltage polarity (i.e., either a positive voltage polarity or a negative voltage polarity) results in a filtered RF signal being transmitted out the end 220 of the inductor 212 with the same voltage polarity. Also, the inductor 212 is magnetically coupled to the inductor 208 such that an RF signal received at the end 220 of the inductor 212 with a voltage polarity (i.e., either a positive voltage polarity or a negative voltage polarity) results in a filtered RF signal being transmitted out the end 217 of the inductor 208 with the same voltage polarity. This is indicated in FIG. 22 by the dot convention where a dot is placed at the end 217 of the inductor 208 and a dot is placed at the end 220 of the inductor 212. By using two independent and adjustable coupling coefficients (i.e., the positive coupling coefficient and the negative coupling coefficient) with the resonator R(1,2) (i.e., the differential resonator), the transfer function of the first tunable RF filter path 66 is provided so as to be fully adjustable. More specifically, the inductors 208, 212 may be magnetically coupled so as to have a low magnetic coupling coefficient through field cancellation, with the variable positive coupling coefficient and the variable negative coupling coefficient. In this case, the inductor 208 and the inductor 212 are arranged such that a mutual magnetic coupling between the inductor 208 and the inductor 212 cancel. Alternatively, the inductor 208 and the inductor 212 are arranged such that the inductor 212 reduces a mutual magnetic coupling coefficient of the inductor 208. With respect to the magnetic coupling coefficient, the variable positive coupling coefficient is a variable positive electric coupling coefficient and the variable negative coupling coefficient is a variable negative electric coupling coefficient. The variable positive electric coupling coefficient and the variable negative electric coupling coefficient oppose each other to create a tunable filter characteristic.

The resonator R(1,2) is operably associated with the resonator R(1,1) such that an energy transfer factor between the resonator R(1,1) and the resonator R(1,2) is less than 10%. A total mutual coupling between the resonator R(1,1) and the

resonator R(**1,2**) is provided by a sum total of the mutual magnetic factor between the resonator R(**1,1**) and the resonator R(**1,2**) and the mutual electric coupling coefficients between the resonator R(**1,1**) and the resonator R(**1,2**). In this embodiment, the mutual magnetic coupling coefficient between the inductor **208** and the inductor **212** is a fixed mutual magnetic coupling coefficient. Although embodiments of the resonators R(**1,1**), R(**1,2**) may be provided so as to provide a variable magnetic coupling coefficient between the resonators R(**1,1**), R(**1,2**), embodiments of the resonators R(**1,1**), R(**1,2**) that provide variable magnetic couplings can be costly and difficult to realize. However, providing variable electric coupling coefficients (i.e., the variable positive electric coupling coefficient and the variable electric negative coupling coefficient) is easier and more economical. Thus, using the cross-coupling capacitive structure C(**P1**) and the cross-coupling capacitive structure C(**N1**) to provide the variable positive electric coupling coefficient and the variable electric negative coupling coefficient is an economical technique for providing a tunable filter characteristic between the resonators R(**1,1**), R(**1,2**). Furthermore, since the mutual magnetic coupling coefficient between the inductor **208** and the inductor **212** is fixed, the first tunable RF filter path **66** has lower insertion losses.

In the embodiment shown in FIG. **22**, the inductor **208** and the **212** inductor are the same size. Alternatively, the inductor **208** and the inductor **212** may be different sizes. For example, the inductor **212** may be smaller than the inductor **208**. By determining a distance between the inductor **208** and the inductor **212**, the magnetic coupling coefficient between the inductor **208** and the inductor **212** can be set. With regard to the inductors **208**, **212** shown in FIG. **22**, the inductor **208** may be a folded inductor configured to generate a first confined magnetic field, while the inductor **212** may be a folded inductor configured to generate a second confined magnetic field. Magnetic field lines of the first confined magnetic field and of the second confined magnetic field that are external to the inductor **208** and inductor **212** are cancelled by opposing magnetic field lines in all directions. When the inductor **208** and the inductor **212** are folded inductors, the folded inductors can be stacked. This allows building the first tunable RF filter path **66** such that several inductors **208**, **212** are stacked. Furthermore, this arrangement allows for a specially sized interconnect structure that electrically connects the inductors **208**, **212** to the capacitive structure **210**, the capacitive structure **214**, the capacitive structure **216**, the cross-coupling capacitive structure C(**P1**), and the cross-coupling capacitive structure C(**N1**). The specially sized interconnect increases the Q factor of the capacitive structure **210**, the capacitive structure **214**, the capacitive structure **216**, the cross-coupling capacitive structure C(**P1**), and the cross-coupling capacitive structure C(**N1**), and allows for precise control of their variable capacitances. Weakly coupled filters can also be realized with planar field cancellation structures.

FIG. **23** illustrates an exemplary embodiment of the first tunable RF filter path **66** in the first RF filter structure **60** shown in FIG. **21**. While the exemplary embodiment shown in FIG. **23** is of the first tunable RF filter path **66**, any of the tunable RF filter paths shown in the first RF filter structure **60** of FIG. **21** may be arranged in accordance with the exemplary embodiment shown in FIG. **23**. The first tunable RF filter path **66** shown in FIG. **23** includes an embodiment of the resonator R(**1,1**) and an embodiment of the resonator R(**1,2**). The resonator R(**1,1**) and the resonator R(**1,2**) are weakly coupled to one another. The embodiment of the resonator R(**1,2**) is the same as the embodiment of the resonator R(**1,2**) shown in FIG. **22**. Thus, the resonator R(**1,2**) shown in FIG. **23** is a

differential resonator that includes the inductor **212**, the capacitive structure **214**, and the capacitive structure **216**. Additionally, like the embodiment of the resonator R(**1,1**) shown in FIG. **22**, the embodiment of the resonator R(**1,1**) shown in FIG. **23** includes the inductor **208** and the capacitive structure **210**. However, in this embodiment, the resonator R(**1,1**) shown in FIG. **23** is a differential resonator and further includes a capacitive structure **224**. More specifically, the end **217** of the inductor **208** is electrically connected to the capacitive structure **210** and the end **218** of the inductor **208** is electrically connected to the capacitive structure **224**. Both the capacitive structure **210** and the capacitive structure **224** are grounded. Like the capacitive structure **210**, the capacitive structure **224** is also a variable capacitive structure, such as a programmable array of capacitors or a varactor. Alternatively, a center tap of an inductor may be grounded. In yet another embodiment, the inductor and a capacitive structure may be RF floating (a low-resistance connection to ground).

The resonator R(**1,1**) and the resonator R(**1,2**) are a pair of weakly coupled resonators. Like the first tunable RF filter path **66** shown in FIG. **22**, the resonator R(**1,1**) and the resonator R(**1,2**) are weakly coupled by providing the inductor **208** and the inductor **212** such that the inductor **208** and the inductor **212** are weakly coupled. Thus, the inductor **208** and the inductor **212** may have a magnetic coupling coefficient that is less than or equal to approximately 0.3. Although the resonator R(**1,1**) and the resonator R(**1,2**) are weakly coupled, a displacement between the inductor **208** and the inductor **212** is less than or equal to half the maximum lateral width of the inductor **212**. As such, the inductor **208** and the inductor **212** are relatively close to one another. The displacement between the inductor **208** and the inductor **212** may be measured from a geometric centroid of the inductor **208** to a geometric centroid of the inductor **212**. The maximum lateral width may be a maximum dimension of the inductor **212** along a plane defined by its largest winding.

The weak coupling between the inductor **208** and the inductor **212** is obtained through topological techniques. For example, the inductor **208** and the inductor **212** may be fully or partially aligned, where winding(s) of the inductor **208** and winding(s) of the inductor **212** are configured to provide weak coupling through cancellation. Alternatively or additionally, a plane defining an orientation of the windings of the inductor **208** and a plane defining an orientation of the windings of the inductor **212** may be fully or partially orthogonal to one another.

The resonator R(**1,2**) is operably associated with the resonator R(**1,1**) such that an energy transfer factor between the resonator R(**1,1**) and the resonator R(**1,2**) is less than 10%. To provide a tuning range to tune a transfer function of the first tunable RF filter path **66** such to provide a fast roll-off from a low-frequency side to a high-frequency side requires changing a sign of the total mutual coupling coefficient between the resonator R(**1,1**) and the resonator R(**1,2**). Like the embodiment of the first tunable RF filter path **66** shown in FIG. **22**, the first tunable RF filter path **66** shown in FIG. **23** includes the cross-coupling capacitive structure C(**P1**) and the cross-coupling capacitive structure C(**N1**). The cross-coupling capacitive structure C(**P1**) and the cross-coupling capacitive structure C(**N1**) are arranged in the same manner described above with respect to FIG. **22**. However, in this embodiment, the first tunable RF filter path **66** shown in FIG. **23** also includes a cross-coupling capacitive structure C(**P2**) and a cross-coupling capacitive structure C(**N2**). The cross-coupling capacitive structure C(**P2**) and the cross-coupling

capacitive structure C(N2) are also embodiments of the cross-coupling capacitive structures C described above with regard to FIG. 21.

As described above with respect to FIG. 22, the cross-coupling capacitive structure C(P1) is electrically connected between the resonator R(1,1) and the resonator R(1,2) so as to provide the positive coupling coefficient (i.e., the variable positive electric coupling coefficient) between the resonator R(1,1) and the resonator R(1,2). Also as described above with respect to FIG. 22, the cross-coupling capacitive structure C(N1) is electrically connected between the resonator R(1,1) and the resonator R(1,2) so as to provide the negative coupling coefficient (i.e., the variable negative electric coupling coefficient) between the resonator R(1,1) and the resonator R(1,2). With regard to the cross-coupling capacitive structure C(P2), the cross-coupling capacitive structure C(P2) is electrically connected between the resonator R(1,1) and the resonator R(1,2) so as to provide another positive coupling coefficient (i.e., another variable positive electric coupling coefficient) between the resonator R(1,1) and the resonator R(1,2). In this embodiment, the cross-coupling capacitive structure C(P2) is electrically connected between the end 218 of the inductor 208 and the end 222 of the inductor 212. The cross-coupling capacitive structure C(P2) is a variable cross-coupling capacitive structure configured to vary the other positive coupling coefficient (i.e., the other variable positive electric coupling coefficient) provided between the resonator R(1,1) and the resonator R(1,2). With regard to the cross-coupling capacitive structure C(N2), the cross-coupling capacitive structure C(N2) is electrically connected between the resonator R(1,1) and the resonator R(1,2) so as to provide another negative coupling coefficient (i.e., another variable negative electric coupling coefficient) between the resonator R(1,1) and the resonator R(1,2). In this embodiment, the cross-coupling capacitive structure C(N2) is electrically connected between the end 218 of the inductor 208 and the end 220 of the inductor 212. The cross-coupling capacitive structure C(N2) is a variable cross-coupling capacitive structure configured to vary the negative coupling coefficient (i.e., the other variable negative electric coupling coefficient) provided between the resonator R(1,1) and the resonator R(1,2). The arrangement of the cross-coupling capacitive structure C(P1), the cross-coupling capacitive structure C(N1), the cross-coupling capacitive structure C(P2), and the cross-coupling capacitive structure C(N2) shown in FIG. 23 is an X-bridge structure.

As shown in FIG. 23, the resonator R(1,2) is operably associated with the resonator R(1,1) such that an energy transfer factor between the resonator R(1,1) and the resonator R(1,2) is less than 10%. The total mutual coupling between the resonator R(1,1) and the resonator R(1,2) is provided by a sum total of the mutual magnetic factor between the resonator R(1,1) and the resonator R(1,2) and the mutual electric coupling coefficients between the resonator R(1,1) and the resonator R(1,2). Thus, in this embodiment, the total mutual coupling between the resonator R(1,1) and the resonator R(1,2) is provided by the sum total of the mutual magnetic coupling coefficient, the variable positive electric coupling coefficient provided by the cross-coupling capacitive structure C(P1), the variable negative electric coupling coefficient provided by the cross-coupling capacitive structure C(N1), the other variable positive electric coupling coefficient provided by the cross-coupling capacitive structure C(P2), and the other variable negative electric coupling coefficient provided by the cross-coupling capacitive structure C(N2).

FIG. 24 illustrates an exemplary embodiment of the first tunable RF filter path 66 in the first RF filter structure 60

shown in FIG. 21. While the exemplary embodiment shown in FIG. 24 is of the first tunable RF filter path 66, any of the tunable RF filter paths shown in the first RF filter structure 60 of FIG. 21 may be arranged in accordance with the exemplary embodiment shown in FIG. 24. The first tunable RF filter path 66 shown in FIG. 24 includes an embodiment of the resonator R(1,1) and an embodiment of the resonator R(1,2). The resonator R(1,1) and the resonator R(1,2) are weakly coupled to one another. The embodiment of the resonator R(1,1) is the same as the embodiment of the resonator R(1,1) shown in FIG. 22. Thus, the resonator R(1,1) shown in FIG. 24 is a single-ended resonator that includes the inductor 208 and the capacitive structure 210. Additionally, like the embodiment of the resonator R(1,2) shown in FIG. 22, the embodiment of the resonator R(1,2) shown in FIG. 24 includes the inductor 212 and the capacitive structure 214. However, in this embodiment, the resonator R(1,2) shown in FIG. 24 is a single-ended resonator. More specifically, the end 220 and the end 222 of the inductor 212 are each electrically connected to the capacitive structure 214, which is grounded.

The resonator R(1,1) and the resonator R(1,2) are a pair of weakly coupled resonators. Like the first tunable RF filter path 66 shown in FIG. 22, the resonator R(1,1) and the resonator R(1,2) are weakly coupled by providing the inductor 208 and the inductor 212 such that the inductor 208 and the inductor 212 are weakly coupled. Thus, the inductor 208 and the inductor 212 may have a magnetic coupling coefficient that is less than or equal to approximately 0.3. Although the resonator R(1,1) and the resonator R(1,2) are weakly coupled, the displacement between the inductor 208 and the inductor 212 is less than or equal to half the maximum lateral width of the inductor 212. As such, the inductor 208 and the inductor 212 are relatively close to one another. The displacement between the inductor 208 and the inductor 212 may be measured from the geometric centroid of the inductor 208 to the geometric centroid of the inductor 212. The maximum lateral width may be a maximum dimension of the inductor 212 along a plane defined by its largest winding. The weak coupling between the inductor 208 and the inductor 212 is obtained through topological techniques. For example, the inductor 208 and the inductor 212 may be fully or partially aligned, where winding(s) of the inductor 208 and winding(s) of the inductor 212 are configured to provide weak coupling through cancellation. Alternatively or additionally, a plane defining an orientation of the windings of the inductor 208 and a plane defining an orientation of the windings of the inductor 212 may be fully or partially orthogonal to one another.

The resonator R(1,2) is operably associated with the resonator R(1,1) such that an energy transfer factor between the resonator R(1,1) and the resonator R(1,2) is less than 10%. To provide a tuning range to tune a transfer function of the first tunable RF filter path 66 and provide a fast roll-off from a low-frequency side to a high-frequency side of the transfer function, the first tunable RF filter path 66 is configured to change a sign of a total mutual coupling coefficient between the resonator R(1,1) and the resonator R(1,2). However, in this embodiment, the first tunable RF filter path 66 shown in FIG. 24 only includes the cross-coupling capacitive structure C(P1), which is electrically connected between the end 217 of the inductor 208 and the end 220 of the inductor 212. As discussed above with respect to FIGS. 22 and 23, the cross-coupling capacitive structure C(P1) is a variable cross-coupling capacitive structure configured to vary the positive coupling coefficient (i.e., the variable positive electric coupling coefficient) provided between the resonator R(1,1) and the resonator R(1,2). Thus, in order to allow for the sign of the

total mutual coupling coefficient between the resonator R(**1,1**) and the resonator R(**1,2**) to be changed, the inductor **208** and the inductor **212** are arranged so as to provide a fixed negative mutual magnetic coupling coefficient between the inductor **208** of the resonator R(**1,1**) and the inductor **212** of the resonator R(**1,2**). As such, varying the variable positive electric coupling coefficient allows for the sign of the total mutual coupling coefficient between the resonator R(**1,1**) and the resonator R(**1,2**) to be changed using only the cross-coupling capacitive structure C(P1).

As such, in this embodiment, the inductor **208** is magnetically coupled to the inductor **212** such that an RF signal received at the end **217** of the inductor **208** with a voltage polarity (i.e., either a positive voltage polarity or a negative voltage polarity) results in a filtered RF signal with the same voltage polarity being transmitted out the end **222** of the inductor **212**. In addition, the inductor **212** is magnetically coupled to the inductor **208** such that an RF signal received at the end **222** of the inductor **212** with a voltage polarity (i.e., either a positive voltage polarity or a negative voltage polarity) results in a filtered RF signal with the same voltage polarity being transmitted out the end **217** of the inductor **208**. This is indicated in FIG. **24** by the dot convention where a dot is placed at the end **217** of the inductor **208** and a dot is placed at the end **222** of the inductor **212**. By using the fixed negative mutual magnetic coupling coefficient and the variable positive electric coupling coefficient, the transfer function of the first tunable RF filter path **66** is provided so to be fully adjustable. The arrangement of the cross-coupling capacitive structure C(P1) shown in FIG. **24** is a single positive bridge structure.

FIG. **25** illustrates another exemplary embodiment of the first tunable RF filter path **66** in the first RF filter structure **60** shown in FIG. **21**. While the exemplary embodiment shown in FIG. **25** is of the first tunable RF filter path **66**, any of the tunable RF filter paths shown in the first RF filter structure **60** of FIG. **21** may be arranged in accordance with the exemplary embodiment shown in FIG. **25**. The first tunable RF filter path **66** shown in FIG. **25** includes an embodiment of the resonator R(**1,1**) and an embodiment of the resonator R(**1,2**). The resonator R(**1,1**) and the resonator R(**1,2**) are weakly coupled to one another. The embodiment of the resonator R(**1,1**) is the same as the embodiment of the resonator R(**1,1**) shown in FIG. **22**. Thus, the resonator R(**1,1**) shown in FIG. **25** is a single-ended resonator that includes the inductor **208** and the capacitive structure **210**, which are arranged in the same manner described above with respect to FIG. **22**. Like the resonator R(**1,2**) shown in FIG. **24**, the resonator R(**1,2**) shown in FIG. **25** is a single-ended resonator that includes the inductor **212** and the capacitive structure **214**. However, the inductor **208** shown in FIG. **25** is magnetically coupled to the inductor **212** such that an RF signal received at the end **217** of the inductor **208** with a voltage polarity (i.e., either a positive voltage polarity or a negative voltage polarity) results in a filtered RF signal with the same voltage polarity being transmitted out the end **220** of the inductor **212**. Also, the inductor **212** shown in FIG. **25** is magnetically coupled to the inductor **208** such that an RF signal received at the end **220** of the inductor **212** with a voltage polarity (i.e., either a positive voltage polarity or a negative voltage polarity) results in a filtered RF signal with the same voltage polarity being transmitted out the end **217** of the inductor **208**. This is indicated in FIG. **25** by the dot convention where a dot is placed at the end **217** of the inductor **208** and a dot is placed at the end **220** of the inductor **212**. In alternative embodiments, the resonator R(**1,2**) is a differential resonator. In yet another alternative

embodiment, the resonator R(**1,1**) is a single-ended resonator while the resonator R(**1,2**) is a differential resonator.

The resonator R(**1,1**) and the resonator R(**1,2**) are a pair of weakly coupled resonators. Like the first tunable RF filter path **66** shown in FIG. **22**, the resonator R(**1,1**) and the resonator R(**1,2**) are weakly coupled by providing the inductor **208** and the inductor **212** such that the inductor **208** and the inductor **212** are weakly coupled. Thus, the inductor **208** and the inductor **212** may have a fixed magnetic coupling coefficient that is less than or equal to approximately 0.3. Although the resonator R(**1,1**) and the resonator R(**1,2**) are weakly coupled, a displacement between the inductor **208** and the inductor **212** is less than or equal to half the maximum lateral width of the inductor **212**. As such, the inductor **208** and the inductor **212** are relatively close to one another. The displacement between the inductor **208** and the inductor **212** may be measured from a geometric centroid of the inductor **208** to a geometric centroid of the inductor **212**. The maximum lateral width may be a maximum dimension of the inductor **212** along a plane defined by its largest winding.

The weak coupling between the inductor **208** and the inductor **212** is obtained through topological techniques. For example, the inductor **208** and the inductor **212** may be fully or partially aligned, where winding(s) of the inductor **208** and winding(s) of the inductor **212** are configured to provide weak coupling through cancellation. Alternatively or additionally, a plane defining an orientation of the windings of the inductor **208** and a plane defining an orientation of the windings of the inductor **212** may be fully or partially orthogonal to one another.

The resonator R(**1,2**) is operably associated with the resonator R(**1,1**) such that an energy transfer factor between the resonator R(**1,1**) and the resonator R(**1,2**) is less than 10%. To provide a tuning range to tune the transfer function of the first tunable RF filter path **66** and to provide a fast roll-off from the low-frequency side to the high-frequency side of the transfer function, the first tunable RF filter path **66** is configured to change the sign of the total mutual coupling coefficient between the resonator R(**1,1**) and the resonator R(**1,2**). In this embodiment, the first tunable RF filter path **66** shown in FIG. **25** includes a cross-coupling capacitive structure C(PH1), a cross-coupling capacitive structure (CNH1), a cross-coupling capacitive structure C(I1), a cross-coupling capacitive structure C(PH2), and a cross-coupling capacitive structure C(NH2). The cross-coupling capacitive structure C(PH1), the cross-coupling capacitive structure (CNH1), the cross-coupling capacitive structure C(I1), the cross-coupling capacitive structure C(PH2), and the cross-coupling capacitive structure C(NH2) are also embodiments of the cross-coupling capacitive structures C described above with regard to FIG. **21**.

The cross-coupling capacitive structure C(PH1) and the cross-coupling capacitive structure C(NH1) are arranged to form a first capacitive voltage divider. The first capacitive voltage divider is electrically connected to the resonator R(**1,1**). More specifically, the cross-coupling capacitive structure C(PH1) is electrically connected between the end **217** of the inductor **208** and a common connection node H1. The cross-coupling capacitive structure C(NH1) is electrically connected between the end **218** of the inductor **208** and the common connection node H1. Additionally, the cross-coupling capacitive structure C(PH2) and the cross-coupling capacitive structure C(NH2) are arranged to form a second capacitive voltage divider. The second capacitive voltage divider is electrically connected to the resonator R(**1,2**). More specifically, the cross-coupling capacitive structure C(PH2) is electrically connected between the end **220** of the inductor

212 and a common connection node H2. The cross-coupling capacitive structure C(NH2) is electrically connected between the end 222 of the inductor 212 and the common connection node H2. As shown in FIG. 25, the cross-coupling capacitive structure C(I1) is electrically connected between the first capacitive voltage divider and the second capacitive voltage divider. More specifically, the cross-coupling capacitive structure C(I1) is electrically connected between the common connection node H1 and the common connection node H2. The arrangement of the cross-coupling capacitive structure C(PH1), the cross-coupling capacitive structure C(NH1), the cross-coupling capacitive structure C(PH2), the cross-coupling capacitive structure C(NH2), and the cross-coupling capacitive structure C(I1) shown in FIG. 25 is an H-bridge structure. In an alternative H-bridge structure, the cross-coupling capacitive structure C(I1) is not provided and instead there is a short between the common connection node H1 and the common connection node H2. In addition, a center tap of the inductor 208 may be grounded and/or the common connection node H1 may be grounded. Finally, a high imped-ance to ground may be provided at the common connection node H1.

With regard to the first capacitive voltage divider, the cross-coupling capacitive structure C(PH1) is a variable cross-cou-pling capacitive structure configured to vary a first variable positive electric coupling coefficient provided between the resonator R(1,1) and the common connection node H1. The cross-coupling capacitive structure C(NH1) is a variable cross-coupling capacitive structure configured to vary a first variable negative electric coupling coefficient provided between the resonator R(1,1) and the common connection node H1. Thus, a mutual electric coupling coefficient of the resonator R(1,1) is approximately equal to the first variable positive electric coupling coefficient and the first variable negative electric coupling coefficient.

With regard to the second capacitive voltage divider, the cross-coupling capacitive structure C(PH2) is a variable cross-coupling capacitive structure configured to vary a sec-ond variable positive electric coupling coefficient provided between the resonator R(1,2) and the common connection node H2. The cross-coupling capacitive structure C(NH2) is a variable cross-coupling capacitive structure configured to vary a second variable negative electric coupling coefficient provided between the resonator R(1,2) and the common con-nection node H2. Thus, a mutual electric coupling coefficient of the resonator R(1,2) is approximately equal to the second variable positive electric coupling coefficient and the second variable negative electric coupling coefficient. Furthermore, the cross-coupling capacitive structure C(I1) is a variable cross-coupling capacitive structure configured to vary a first variable intermediate electric coupling coefficient provided between the common connection node H1 and the common connection node H2. The first tunable RF filter path 66 shown in FIG. 25 thus has a total mutual coupling coefficient between the resonator R(1,1) and the resonator R(1,2) equal to the sum total of the mutual magnetic coupling coefficient between the inductor 208 and the inductor 212, the mutual electric coupling coefficient of the resonator R(1,1), the mutual electric coupling coefficient of the resonator R(1,2), and the first variable intermediate electric coupling coeffi-cient provided between the common connection node H1 and the common connection node H2. In alternative embodi-ments, cross-coupling capacitive structures with fixed capaci-tances are provided.

In one embodiment, the cross-coupling capacitive struc-ture C(PH1), the cross-coupling capacitive structure C(NH1), the cross-coupling capacitive structure C(PH2), the cross-

coupling capacitive structure C(NH2), and the cross-coupling capacitive structure C(I1) may each be provided as a varactor. However, the cross-coupling capacitive structure C(PH1), the cross-coupling capacitive structure C(NH1), the cross-cou-pling capacitive structure C(PH2), the cross-coupling capaci-tive structure C(NH2), and the cross-coupling capacitive structure C(I1) may each be provided as a programmable array of capacitors in order to reduce insertion losses and improve linearity. The cross-coupling capacitive structure C(PH1), the cross-coupling capacitive structure C(NH1), the cross-coupling capacitive structure C(PH2), the cross-cou-pling capacitive structure C(NH2), and the cross-coupling capacitive structure C(I1) can also be any combination of suitable variable cross-coupling capacitive structures, such as combinations of varactors and programmable arrays of capacitors. Although the H-bridge structure can provide good linearity and low insertion losses, the H-bridge structure can also suffer from common-mode signal transfer.

FIG. 26 illustrates yet another exemplary embodiment of the first tunable RF filter path 66 in the first RF filter structure 60 shown in FIG. 21. While the exemplary embodiment shown in FIG. 26 is of the first tunable RF filter path 66, any of the tunable RF filter paths shown in the first RF filter structure 60 of FIG. 21 may be arranged in accordance with the exemplary embodiment shown in FIG. 26. The first tun-able RF filter path 66 shown in FIG. 26 can be used to ameliorate the common-mode signal transfer of the H-bridge structure shown in FIG. 25. More specifically, the first tunable RF filter path 66 shown in FIG. 26 includes the same embodi-ment of the resonator R(1,1) and the same embodiment of the resonator R(1,2) described above with respect to FIG. 25. Furthermore, the first tunable RF filter path 66 shown in FIG. 26 includes the first capacitive voltage divider with the cross-coupling capacitive structure C(PH1) and the cross-coupling capacitive structure C(NH1) described above with respect to FIG. 25, the second capacitive voltage divider with the cross-coupling capacitive structure C(PH2) and the cross-coupling capacitive structure (CNH2) described above with respect to FIG. 25, and the cross-coupling capacitive structure C(I1) described above with respect to FIG. 25. However, in this embodiment, the first tunable RF filter path 66 shown in FIG. 26 also includes a cross-coupling capacitive structure C(PH3), a cross-coupling capacitive structure (CNH3), a cross-coupling capacitive structure C(I2), a cross-coupling capacitive structure C(PH4), and a cross-coupling capacitive structure C(NH4). The cross-coupling capacitive structure C(PH3), the cross-coupling capacitive structure (CNH3), the cross-coupling capacitive structure C(I2), the cross-coupling capacitive structure C(PH4), and the cross-coupling capaci-tive structure C(NH4) are also embodiments of the cross-coupling capacitive structures C described above with regard to FIG. 21.

As shown in FIG. 26, the cross-coupling capacitive struc-ture C(PH3) and the cross-coupling capacitive structure C(NH3) are arranged to form a third capacitive voltage divider. The third capacitive voltage divider is electrically connected to the resonator R(1,1). More specifically, the cross-coupling capacitive structure C(PH3) is electrically connected between the end 217 of the inductor 208 and a common connection node H3. The cross-coupling capacitive structure C(NH3) is electrically connected between the end 218 of the inductor 208 and the common connection node H3. Additionally, the cross-coupling capacitive structure C(PH4) and the cross-coupling capacitive structure C(NH4) are arranged to form a fourth capacitive voltage divider. The fourth capacitive voltage divider is electrically connected to the resonator R(1,2). More specifically, the cross-coupling

capacitive structure C(PH4) is electrically connected between the end 220 of the inductor 212 and a common connection node H4. The cross-coupling capacitive structure C(NH4) is electrically connected between the end 222 of the inductor 212 and the common connection node H4. As shown in FIG. 26, the cross-coupling capacitive structure C(I2) is electrically connected between first capacitive voltage divider and the second capacitive voltage divider. More specifically, the cross-coupling capacitive structure C(I2) is electrically connected between the common connection node H3 and the common connection node H4. Alternatively, the cross-coupling capacitive structure C(I1) and the cross-coupling capacitive structure C(I2) can be replaced with shorts. The arrangement of the cross-coupling capacitive structure C(PH1), the cross-coupling capacitive structure C(NH1), the cross-coupling capacitive structure C(PH2), the cross-coupling capacitive structure C(NH2), the cross-coupling capacitive structure C(I1), the cross-coupling capacitive structure C(PH3), the cross-coupling capacitive structure C(NH3), the cross-coupling capacitive structure C(PH4), the cross-coupling capacitive structure C(NH4), and the cross-coupling capacitive structure C(I2) shown in FIG. 26 is a double H-bridge structure.

With regard to the third capacitive voltage divider, the cross-coupling capacitive structure C(PH3) is a variable cross-coupling capacitive structure configured to vary a third variable positive electric coupling coefficient provided between the resonator R(1,1) and the common connection node H3. The cross-coupling capacitive structure C(NH3) is a variable cross-coupling capacitive structure configured to vary a third variable negative electric coupling coefficient provided between the resonator R(1,1) and the common connection node H3. Thus, a mutual electric coupling coefficient of the resonator R(1,1) is approximately equal to the first variable positive electric coupling coefficient, the third variable positive electric coupling coefficient, the first variable negative electric coupling coefficient and the third variable negative electric coupling coefficient.

With regard to the fourth capacitive voltage divider, the cross-coupling capacitive structure C(PH4) is a variable cross-coupling capacitive structure configured to vary a fourth variable positive electric coupling coefficient provided between the resonator R(1,2) and the common connection node H4. The cross-coupling capacitive structure C(NH4) is a variable cross-coupling capacitive structure configured to vary a fourth variable negative electric coupling coefficient provided between the resonator R(1,2) and the common connection node H4. Thus, a mutual electric coupling coefficient of the resonator R(1,2) is approximately equal to the second variable positive electric coupling coefficient, the fourth variable positive coupling coefficient, the second variable negative coupling coefficient, and the fourth variable negative electric coupling coefficient. Furthermore, the cross-coupling capacitive structure C(I2) is a variable cross-coupling capacitive structure configured to vary a second variable intermediate electric coupling coefficient provided between the common connection node H3 and the common connection node H4. The first tunable RF filter path 66 shown in FIG. 26 thus has a total mutual coupling coefficient between the resonator R(1,1) and the resonator R(1,2) equal to the sum total of the mutual magnetic coupling coefficient between the inductor 208 and the inductor 212, the mutual electric coupling coefficient of the resonator R(1,1), the mutual electric coupling coefficient of the resonator R(1,2), the first variable intermediate electric coupling coefficient provided between the common connection node H1 and the common connection node H2 and the second variable intermediate electric coupling

coefficient provided between the common connection node H3 and the common connection node H4. The double H-bridge structure thus includes two H-bridge structures. The two H-bridge structures allow for common-mode signal transfers of the two H-bridge structures to oppose one another and thereby be reduced and even cancelled.

FIG. 27 illustrates still another exemplary embodiment of the first tunable RF filter path 66 in the first RF filter structure 60 shown in FIG. 21. While the exemplary embodiment shown in FIG. 27 is of the first tunable RF filter path 66, any of the tunable RF filter paths shown in the first RF filter structure 60 of FIG. 21 may be arranged in accordance with the exemplary embodiment shown in FIG. 27. The first tunable RF filter path 66 shown in FIG. 27 includes the same embodiment of the resonator R(1,1) and the same embodiment of the resonator R(1,2) described above with respect to FIG. 22. In addition, the first tunable RF filter path 66 shown in FIG. 27 includes the cross-coupling capacitive structure C(P1) and the cross-coupling capacitive structure (CN1) that form the V-bridge structure described above with respect to FIG. 22. However, the first tunable RF filter path 66 shown in FIG. 27 further includes a resonator R(1,3) and a resonator R(1,4). More specifically, the resonator R(1,3) includes an inductor 226, a capacitive structure 228, and a capacitive structure 230. The resonator R(1,4) includes an inductor 232 and a capacitive structure 234.

With regard to the resonator R(1,3), the inductor 226 is electrically connected between the capacitive structure 228 and the capacitive structure 230. More specifically, the inductor 226 has an end 236 and an end 238, which are disposed opposite to one another. The end 236 is electrically connected to the capacitive structure 228 and the end 238 is electrically connected to the capacitive structure 230. Both the capacitive structure 228 and the capacitive structure 230 are grounded. Thus, the resonator R(1,3) is a differential resonator. In this embodiment, each of the capacitive structure 228 and the capacitive structure 230 is a variable capacitive structure.

With regard to the resonator R(1,4), the inductor 232 and the capacitive structure 234 are electrically connected in parallel. More specifically, the inductor 232 has an end 240 and an end 242, which are disposed opposite to one another. The ends 240, 242 are each electrically connected to the capacitive structure 234, which is grounded. Thus, the resonator R(1,4) is a single-ended resonator.

In this embodiment, the resonator R(1,1), the resonator R(1,2), the resonator R(1,3), and the resonator R(1,4) are all weakly coupled to one another. The resonator R(1,3) and the resonator R(1,4) are weakly coupled by providing the inductor 226 and the inductor 232 such that the inductor 226 and the inductor 232 are weakly coupled. The resonators R(1,1), R(1, 2), R(1,3), and R(1,4) are each operably associated with one another such that energy transfer factors between the resonators R(1,1), R(1,2), R(1,3), and R(1,4) are less than 10%. Although the resonator R(1,3) and the resonator R(1,4) are weakly coupled, the inductor 232 has a maximum lateral width and a displacement between the inductor 226 and the inductor 232 is less than or equal to half the maximum lateral width of the inductor 232. As such, the inductor 226 and the inductor 232 are relatively close to one another. The displacement between the inductor 226 and the inductor 232 may be measured from a geometric centroid of the inductor 226 to a geometric centroid of the inductor 232. The maximum lateral width may be a maximum dimension of the inductor 232 along a plane defined by its largest winding. The weak coupling between the inductor 226 and the inductor 232 is obtained through topological techniques. For example, the inductor 226 and the inductor 232 may be fully or partially

aligned, where winding(s) of the inductor 226 and winding(s) of the inductor 232 are configured to provide weak coupling through cancellation. Alternatively or additionally, a plane defining an orientation of the windings of the inductor 226 and a plane defining an orientation of the windings of the inductor 232 may be fully or partially orthogonal to one another.

In some embodiments, all of the inductors 208, 212, 226, 232 are provided such that displacements between each of the inductors 208, 212, 226, 232 are less than or equal to half the maximum lateral width of the inductor 212. Alternatively, in other embodiments, only a proper subset of the inductors 208, 212, 226, 232 has displacements that are less than or equal to half the maximum lateral width of the inductor 212. For example, while the displacement between the inductor 208 and the inductor 212 may be less than or equal to half the maximum lateral width of the inductor 212 and the displacement between the inductor 226 and the inductor 232 may be less than or equal to half the maximum lateral width of the inductor 232, the displacements from the inductor 208 and the inductor 212 to the inductor 226 and the inductor 232 may each be greater than half the maximum lateral width of the inductor 212 and half the maximum lateral width of the inductor 232.

The inductors 208, 212, 226, and 232 are magnetically coupled to the each other such that an RF signal received at the end 217 of the inductor 208 with a voltage polarity (i.e., either a positive voltage polarity or a negative voltage polarity) results in filtered RF signals with the same voltage polarity being transmitted out the end 220 of the inductor 212, the end 236 of the inductor 226, and the end 240 of the inductor 232. Also, the inductors 208, 212, 226, and 232 are magnetically coupled to the each other such that an RF signal received at the end 240 of the inductor 232 with a voltage polarity (i.e., either a positive voltage polarity or a negative voltage polarity) results in filtered RF signals with the same voltage polarity being transmitted out the end 217 of the inductor 208, the end 220 of the inductor 212, and the end 236 of the inductor 226. This is indicated in FIG. 27 by the dot convention where a dot is placed at the end 217 of the inductor 208, a dot is placed at the end 220 of the inductor 212, a dot is placed at the end 236 of the inductor 226, and a dot is placed at the end 240 of the inductor 232.

The first tunable RF filter path 66 shown in FIG. 27 includes a cross-coupling capacitive structure C(P3), a cross-coupling capacitive structure C(N3), a cross-coupling capacitive structure C(P4), and a cross-coupling capacitive structure C(N4) electrically connected between the resonator R(1,2) and the resonator R(1,3). With respect to the resonator R(1,2) and the resonator R(1,3), the cross-coupling capacitive structure C(P3), the cross-coupling capacitive structure C(N3), the cross-coupling capacitive structure C(P4) and the cross-coupling capacitive structure C(N4) are arranged to have the X-bridge structure described above with respect to FIG. 23. Thus, the cross-coupling capacitive structure C(P3) is electrically connected between the end 220 and the end 236 so as to provide a variable positive electric coupling coefficient between the resonator R(1,2) and the resonator R(1,3). The cross-coupling capacitive structure C(P3) is a variable cross-coupling capacitive structure configured to vary the variable positive electric coupling coefficient provided between the resonator R(1,2) and the resonator R(1,3). Also, the cross-coupling capacitive structure C(N3) is electrically connected between the end 220 and the end 238 so as to provide a variable negative electric coupling coefficient between the resonator R(1,2) and the resonator R(1,3). The cross-coupling capacitive structure C(N3) is a variable cross-coupling

capacitive structure configured to vary the variable negative electric coupling coefficient provided between the resonator R(1,2) and the resonator R(1,3).

Additionally, the cross-coupling capacitive structure C(P4) is electrically connected between the end 222 and the end 238 so as to provide another variable positive electric coupling coefficient between the resonator R(1,2) and the resonator R(1,3). The cross-coupling capacitive structure C(P4) is a variable cross-coupling capacitive structure configured to vary the other variable positive electric coupling coefficient provided between the resonator R(1,2) and the resonator R(1, 3). Finally, the cross-coupling capacitive structure C(N4) is electrically connected between the end 222 and the end 236 so as to provide another variable negative electric coupling coefficient between the resonator R(1,2) and the resonator R(1,3). The cross-coupling capacitive structure C(N4) is a variable cross-coupling capacitive structure configured to vary the other variable negative electric coupling coefficient provided between the resonator R(1,2) and the resonator R(1,3).

With respect to the resonator R(1,3) and the resonator R(1,4), the first tunable RF filter path 66 shown in FIG. 27 includes a cross-coupling capacitive structure C(P5) and a cross-coupling capacitive structure C(N5) electrically connected between the resonator R(1,3) and the resonator R(1,4). With respect to the resonator R(1,3) and the resonator R(1,4), the cross-coupling capacitive structure C(P5) and the cross-coupling capacitive structure C(N5) are arranged to have the V-bridge structure described above with respect to FIG. 22. Thus, the cross-coupling capacitive structure C(P5) is electrically connected between the end 236 and the end 240 so as to provide a variable positive electric coupling coefficient between the resonator R(1,3) and the resonator R(1,4). The cross-coupling capacitive structure C(P5) is a variable cross-coupling capacitive structure configured to vary the variable positive electric coupling coefficient provided between the resonator R(1,3) and the resonator R(1,4). Also, the cross-coupling capacitive structure C(N5) is electrically connected between the end 238 and the end 240 so as to provide a variable negative electric coupling coefficient between the resonator R(1,3) and the resonator R(1,4). The cross-coupling capacitive structure C(N5) is a variable cross-coupling capacitive structure configured to vary the variable negative electric coupling coefficient provided between the resonator R(1,3) and the resonator R(1,4).

The embodiment of first RF filter structure 60 shown in FIG. 27 also includes a cross-coupling capacitive structure C(P6), a cross-coupling capacitive structure C(N6), a cross-coupling capacitive structure C(P7), a cross-coupling capacitive structure C(N7), and a cross-coupling capacitive structure C(P8). With respect to the resonator R(1,1) and the resonator R(1,3), the cross-coupling capacitive structure C(P6) and the cross-coupling capacitive structure C(N6) are each electrically connected between the resonator R(1,1) and the resonator R(1,3). The cross-coupling capacitive structure C(P6) is electrically connected between the end 217 and the end 236 so as to provide a variable positive electric coupling coefficient between the resonator R(1,1) and the resonator R(1,3). The cross-coupling capacitive structure C(P6) is a variable cross-coupling capacitive structure configured to vary the variable positive electric coupling coefficient provided between the resonator R(1,1) and the resonator R(1,3). Also, the cross-coupling capacitive structure C(N6) is electrically connected between the end 217 and the end 238 so as to provide a variable negative electric coupling coefficient between the resonator R(1,1) and the resonator R(1,3). The cross-coupling capacitive structure C(N6) is a variable cross-coupling capacitive structure configured to vary the variable

negative electric coupling coefficient provided between the resonator R(1,1) and the resonator R(1,3).

With respect to the resonator R(1,2) and the resonator R(1,4), the cross-coupling capacitive structure C(P7) and the cross-coupling capacitive structure C(N7) are each electrically connected between the resonator R(1,2) and the resonator R(1,4). The cross-coupling capacitive structure C(P7) is electrically connected between the end 220 and the end 240 so as to provide a variable positive electric coupling coefficient between the resonator R(1,2) and the resonator R(1,4). The cross-coupling capacitive structure C(P7) is a variable cross-coupling capacitive structure configured to vary the variable positive electric coupling coefficient provided between resonator R(1,2) and the resonator R(1,4). Also, the cross-coupling capacitive structure C(N7) is electrically connected between the end 222 and the end 240 so as to provide a variable negative electric coupling coefficient between the resonator R(1,2) and the resonator R(1,4). The cross-coupling capacitive structure C(N7) is a variable cross-coupling capacitive structure configured to vary the variable negative electric coupling coefficient provided between the resonator R(1,2) and the resonator R(1,4).

With respect to the resonator R(1,1) and the resonator R(1,4), the cross-coupling capacitive structure C(P8) is electrically connected between the resonator R(1,1) and the resonator R(1,4). The cross-coupling capacitive structure C(P8) is electrically connected between the end 217 and the end 240 so as to provide a variable positive electric coupling coefficient between the resonator R(1,1) and the resonator R(1,4). The cross-coupling capacitive structure C(P8) is a variable cross-coupling capacitive structure configured to vary the variable positive electric coupling coefficient provided between the resonator R(1,1) and the resonator R(1,4).

Furthermore, in this embodiment, a variable capacitive structure 244 is electrically connected in series between the terminal 200 and the resonator R(1,1). The variable capacitive structure 244 is configured to vary a variable impedance of the first tunable RF filter path 66 as measured into the terminal 200 in order to match a source or a load impedance at the terminal 200. In addition, a variable capacitive structure 245 is electrically connected in series between the resonator R(1, 4) and the terminal 202. The variable capacitive structure 245 is configured to vary a variable impedance of the first tunable RF filter path 66 as seen into the terminal 202 in order to match a source or a load impedance at the terminal 202.

FIGS. 28A through 28D illustrate different embodiments of the first RF filter structure 60, wherein each of the embodiments has different combinations of input terminals and output terminals. The first RF filter structure 60 can have various topologies. For example, the embodiment of the first RF filter structure 60 shown in FIG. 28A has a single input terminal IN and an integer number i of output terminals OUT$_1$-OUT$_i$. As will be discussed below, the first RF filter structure 60 may define various tunable RF filter paths (e.g., the first tunable RF filter path 66, the second tunable RF filter path 68, the third tunable RF filter path 110, the fourth tunable RF filter path 112, the fifth tunable RF filter path 122, and the sixth tunable RF filter path 124 shown in FIGS. 4, 8, 11, 12, and 14-20) that may be used to receive different RF signals at the input terminal IN and transmit a different filtered RF signal from each of the output terminals OUT$_1$-OUT$_i$. As such, the first RF filter structure 60 shown in FIG. 28A may be specifically configured to provide Single Input Multiple Output (SIMO) operations.

With regard to the embodiment of the first RF filter structure 60 shown in FIG. 28B, the first RF filter structure 60 has an integer number j of input terminals IN$_1$-IN$_j$ and a single

output terminal OUT. As will be discussed below, the first RF filter structure 60 may define various tunable RF filter paths (e.g., the first tunable RF filter path 66, the second tunable RF filter path 68, the third tunable RF filter path 110, the fourth tunable RF filter path 112, the fifth tunable RF filter path 122, and the sixth tunable RF filter path 124 shown in FIGS. 4, 8, 11, 12, and 14-20) that may be used to receive a different RF signal at each of the input terminals IN$_1$-IN$_j$ and transmit different filtered RF signals from the single output terminal OUT. As such, the first RF filter structure 60 shown in FIG. 28B may be specifically configured to provide Multiple Input Single Output (MISO) operations.

With regard to the embodiment of the first RF filter structure 60 shown in FIG. 28C, the first RF filter structure 60 has a single input terminal IN and a single output terminal OUT. As will be discussed below, the first RF filter structure 60 may define various tunable RF filter paths (e.g., the first tunable RF filter path 66, the second tunable RF filter path 68, the third tunable RF filter path 110, the fourth tunable RF filter path 112, the fifth tunable RF filter path 122, and the sixth tunable RF filter path 124 shown in FIGS. 4, 8, 11, 12, and 14-20) that may be used to receive different RF signals at the single input terminal IN and transmit different filtered RF signals from the output terminal OUT. As such, the first RF filter structure 60 shown in FIG. 28A may be specifically configured to provide Single Input Single Output (SISO) operations.

With regard to the embodiment of the first RF filter structure 60 shown in FIG. 28D, the first RF filter structure 60 has the input terminals IN$_1$-IN$_j$ and the output terminals OUT$_1$-OUT$_i$. As will be discussed below, the first RF filter structure 60 may define various tunable RF filter paths (e.g., the first tunable RF filter path 66, the second tunable RF filter path 68, the third tunable RF filter path 110, the fourth tunable RF filter path 112, the fifth tunable RF filter path 122, and the sixth tunable RF filter path 124 shown in FIGS. 4, 8, 11, 12, and 14-20) that may be used to receive a different RF signal at each of the input terminal IN$_1$-IN$_j$ and transmit a different filtered RF signal from each of the output terminals OUT$_1$-OUT$_i$.

FIG. 29 illustrates another embodiment of the first RF filter structure 60. The first RF filter structure 60 shown in FIG. 29 includes one embodiment of the first tunable RF filter path 66 and one embodiment of the second tunable RF filter path 68. The first tunable RF filter path 66 includes the resonator R(1,1) and the resonator R(1,2). The resonator R(1,1) and the resonator R(1,2) are thus a first pair of weakly coupled resonators in the first tunable RF filter path 66. The second tunable RF filter path 68 includes the resonator R(2,1) and the resonator R(2,2). The resonator R(2,1) and the resonator R(2,2) are thus a second pair of weakly coupled resonators in the second tunable RF filter path 68.

As explained in further detail below, a set S of cross-coupling capacitive structures is electrically connected between the resonator R(1,1), the resonator R(1,2), the resonator R(2,1), and the resonator R(2,2) in the first tunable RF filter path 66 and the second tunable RF filter path 68. More specifically, the set S includes a cross-coupling capacitive structure C(PM1), a cross-coupling capacitive structure C(PM2), a cross-coupling capacitive structure C(PM3), a cross-coupling capacitive structure C(PM4), a cross-coupling capacitive structure C(NM1), and a cross-coupling capacitive structure C(NM2). The set S of cross-coupling capacitive structures interconnects the resonator R(1,1), the resonator R(1,2), the resonator R(2,1), and the resonator R(2, 2) so that the first RF filter structure 60 shown in FIG. 29 is a matrix (in this embodiment, a 2×2 matrix) of the resonators R. In alternative embodiments, some of the cross-coupling

capacitive structures C(PM1), C(PM2), C(PM3), C(PM4), C(NM1), and C(NM2) may be omitted depending on the filter transfer function to be provided.

Unlike in the embodiment of the first RF filter structure **60** shown in FIG. **21**, in this embodiment, the first tunable RF filter path **66** and the second tunable RF filter path **68** are not independent of one another. The set S of cross-coupling capacitive structures thus provides for additional tunable RF filter paths to be formed from the resonator R(**1,1**), the resonator R(**1,2**), the resonator R(**2,1**), and the resonator R(**2,2**). As discussed in further detail below, the arrangement of the first RF filter structure **60** shown in FIG. **29** can be used to realize examples of each of the embodiments of the first RF filter structure **60** shown in FIGS. **28A-28D**.

The cross-coupling capacitive structure C(PM1) is electrically connected within the first tunable RF filter path **66**, while the cross-coupling capacitive structure C(PM4) is electrically connected within the second tunable RF filter path **68**. More specifically, the cross-coupling capacitive structure C(PM1) is electrically connected between the resonator R(**1, 1**) and the resonator R(**1,2**) in the first tunable RF filter path **66**. The cross-coupling capacitive structure C(PM1) is a variable cross-coupling capacitive structure configured to provide and vary a (e.g., positive or negative) electric coupling coefficient between the resonator R(**1,1**) and the resonator R(**1,2**). The cross-coupling capacitive structure C(PM4) is a variable cross-coupling capacitive structure configured to provide and vary a (e.g., positive or negative) electric coupling coefficient between the resonator R(**2,1**) and the resonator R(**2,2**) in the second tunable RF filter path **68**.

To provide additional tunable RF filter paths, the cross-coupling capacitive structure C(PM2), the cross-coupling capacitive structure C(PM3), the cross-coupling capacitive structure C(NM1), and the cross-coupling capacitive structure C(NM2) are each electrically connected between the first tunable RF filter path **66** and the second tunable RF filter path **68**. The cross-coupling capacitive structure C(PM2) is a variable cross-coupling capacitive structure configured to provide and vary a (e.g., positive or negative) electric coupling coefficient between the resonator R(**1,2**) and the resonator R(**2,2**). The cross-coupling capacitive structure C(PM3) is a variable cross-coupling capacitive structure configured to provide and vary a (e.g., positive or negative) electric coupling coefficient between the resonator R(**1,1**) and the resonator R(**2,1**). The cross-coupling capacitive structure C(NM1) is a variable cross-coupling capacitive structure configured to provide and vary a (e.g., positive or negative) electric coupling coefficient between the resonator R(**1,1**) and the resonator R(**2,2**). The cross-coupling capacitive structure C(NM2) is a variable cross-coupling capacitive structure configured to provide and vary a (e.g., positive or negative) electric coupling coefficient between the resonator R(**1,2**) and the resonator R(**2,1**).

The first tunable RF filter path **66** is electrically connected between the input terminal IN₁ and the output terminal OUT₁. In addition, the second tunable RF filter path **68** is electrically connected between an input terminal IN₂ and an output terminal OUT₂. Accordingly, the first RF filter structure **60** shown in FIG. **29** is an embodiment of the first RF filter structure **60** shown in FIG. **28D**. However, the input terminal IN₂ and the output terminal OUT₁ are optional and may be excluded in other embodiments. For example, if the input terminal IN₂ were not provided, but the output terminal OUT₁ and the output terminal OUT₂ were provided, the first RF filter structure **60** shown in FIG. **29** would be provided as an embodiment of the first RF filter structure **60** shown in FIG. **28A**. It might, for example, provide a diplexing or a duplexing

function. Furthermore, more than two input terminals or output terminals can be provided. Some examples include embodiments of the first RF filter structure **60** used for triplexing, quadplexing, herplexing, and providing FDD and carrier aggregation.

The first tunable RF filter path **66** still provides a path between the input terminal IN₁ and the output terminal OUT₁. However, assuming that the input terminal IN₂ is not provided for SIMO operation, the cross-coupling capacitive structure C(NM1) is electrically connected between the first tunable RF filter path **66** and the second tunable RF filter path **68** to define a first additional tunable RF filter path between the input terminal IN₁ and the output terminal OUT₂. The first additional tunable RF filter path is thus provided by a portion of the first tunable RF filter path **66** and a portion of the second tunable RF filter path **68**. More specifically, the first additional tunable RF filter path includes the resonator R(**1,1**) and the resonator R(**2,2**). The first additional tunable RF filter path also includes the cross-coupling capacitive structure C(NM1) that is electrically connected between the resonator R(**1,1**) and the resonator R(**1,2**). A second additional tunable RF filter path, a third additional tunable RF filter path, a fourth additional tunable RF filter path, and a fifth additional tunable RF filter path are also defined from the input terminal IN₁ to the output terminal OUT₂. The second additional tunable RF filter path includes the resonator R(**1,1**), the cross-coupling capacitive structure C(PM1), the resonator R(**1,2**), the cross-coupling capacitive C(PM2), and the resonator R(**2,2**). Additionally, the third additional tunable RF filter path includes the resonator R(**1,1**), the cross-coupling capacitive structure C(PM3), the resonator R(**2,1**), the cross-coupling capacitive C(PM4), and the resonator R(**2,2**). The fourth additional tunable RF filter path includes the resonator R(**1,1**), the cross-coupling capacitive structure C(PM1), the resonator R(**1,2**), the cross-coupling capacitive C(NM2), the resonator R(**2,1**), the cross-coupling capacitive structure C(PM4), and the resonator R(**2,2**). Finally, the fifth additional tunable RF filter path includes the resonator R(**1,1**), the cross-coupling capacitive structure C(PM3), the resonator R(**2,1**), the cross-coupling capacitive C(NM2), the resonator R(**1,2**), the cross-coupling capacitive structure C(PM2), and the resonator R(**2,2**).

If the output terminal OUT₁ were not provided, but the input terminal IN₁ and the input terminal IN₂ were provided, the first RF filter structure **60** shown in FIG. **29** would be provided as an embodiment of the first RF filter structure **60** shown in FIG. **28B**. In this case, the second tunable RF filter path **68** still provides a path between the input terminal IN₂ and the output terminal OUT₂. However, assuming that the output terminal OUT₁ is not provided for MISO operation, the first additional tunable RF filter path, the second additional tunable RF filter path, the third additional tunable RF filter path, the fourth additional tunable RF filter path, and the fifth additional tunable RF filter path would provide the paths from the input terminal IN₁ to the output terminal OUT₂.

Finally, if the input terminal IN₂ and the output terminal OUT₂ were not provided, the first RF filter structure **60** shown in FIG. **29** would be provided as an embodiment of the first RF filter structure **60** shown in FIG. **28C**. In this case, the second tunable RF filter path **68** still provides a path between the input terminal IN₂ and the output terminal OUT₂. However, assuming that the output terminal IN₁ is not provided for MISO operation, the first additional tunable RF filter path, the second additional tunable RF filter path, the third additional tunable RF filter path, the fourth additional tunable RF filter path, and the fifth additional tunable RF filter path would provide the paths from the input terminal IN₁ to the output terminal OUT₂. This may constitute a SISO filter imple-

mented with an array to allow for a large number of signal paths and thus create one or more notches in the transfer function.

With regard to the resonators R(**1,1**), R(**1,2**), R(**2,1**), R(**2,2**) shown in FIG. **29**, the resonators R(**1,1**), R(**1,2**), R(**2,1**), R(**2, 2**) may each be single-ended resonators, differential resonators, or different combinations of single-ended resonators and differential resonators. The resonator R(**1,1**) and the resonator R(**1,2**) in the first tunable RF filter path **66** may each be provided in accordance with any of the embodiments of the resonator R(**1,1**) and the resonator R(**1,2**) described above with respect to FIGS. **22-27**. For example, the resonator R(**1, 1**) may include the inductor **208** (see FIG. **24**) and the capacitive structure **210** (see FIG. **24**). The resonator R(**1,2**) may include the inductor **212** and the capacitive structure **214** (see FIG. **24**). The resonator R(**2,1**) may include an inductor (like the inductor **208** in FIG. **24**) and a capacitive structure (like the capacitive structure **210** shown in FIG. **24**). The resonator R(**2,2**) may include an inductor (like the inductor **212** in FIG. **24**) and a capacitive structure (like the capacitive structure **214** shown in FIG. **24**).

Additionally, one or more of the resonators R(**1,1**), R(**1,2**) in the first tunable RF filter path **66** and one or more of the resonators R(**2,1**), R(**2,2**) in the second tunable RF filter path **68** may be weakly coupled. Thus, the resonators R(**1,1**), R(**1, 2**), R(**2,1**), R(**2,2**) may be operably associated with one another such that an energy transfer factor between each of the resonators R(**1,1**), R(**1,2**), R(**2,1**), R(**2,2**) is less than 10%. Alternatively, the energy transfer factor between only a subset of the resonators R(**1,1**), R(**1,2**), R(**2,1**), R(**2,2**) is less than 10%. In addition, in at least some embodiments, not all of the resonators R(**1,1**), R(**1,2**), R(**2,1**), R(**2,2**) are weakly coupled to one another.

In this embodiment, the inductor **208** (see FIG. **24**) of the resonator R(**1,1**), the inductor **212** (see FIG. **24**) of the resonator R(**1,2**), the inductor of the resonator R(**2,1**), and the inductor of the resonator R(**2,2**) may all be weakly coupled to one another. In some embodiments, displacements between the inductor **208** (see FIG. **24**) of the resonator R(**1,1**), the inductor **212** (see FIG. **24**) of the resonator R(**1,2**), the inductor of the resonator R(**2,1**), and the inductor of the resonator R(**2,2**) may all be less than or equal to half the maximum lateral width of the inductor **212**. Alternatively, in other embodiments, only a proper subset of the inductor **208** (see FIG. **24**) of the resonator R(**1,1**), the inductor **212** (see FIG. **24**) of the resonator R(**1,2**), the inductor of the resonator R(**2,1**), and the inductor of the resonator R(**2,2**) may have displacements that are less than or equal to half the maximum lateral width of the inductor **212**.

FIG. **30** illustrates yet another embodiment of the first RF filter structure **60**. The first RF filter structure **60** includes the resonators R described above with respect to FIG. **21**. The resonators R of the first RF filter structure **60** shown in FIG. **30** are arranged as a two-dimensional matrix of the resonators R. In this embodiment, the first RF filter structure **60** includes an embodiment of the first tunable RF filter path **66**, an embodiment of the second tunable RF filter path **68**, an embodiment of the third tunable RF filter path **110**, and an embodiment of the fourth tunable RF filter path **112**. Thus, the integer M for the first RF filter structure **60** shown in FIG. **30** is four (4) or greater. Additionally, the integer N for the first RF filter structure **60** shown in FIG. **30** is 3 or greater. Note that in alternative embodiments, the integer M may be two (2) or greater and the integer N may be two (2) or greater. It should be noted that in alternative embodiments the number of resonators R in each row and column may be the same or different.

In the embodiment of the first RF filter structure **60** shown in FIG. **30**, the first tunable RF filter path **66** includes the resonator R(**1,1**), the resonator R(**1,2**), and one or more additional resonators R, such as the resonator R(**1,N**), since the integer N is 3 or greater. All of the weakly coupled resonators R(**1,1**) through R(**1,N**) are weakly coupled to one another. Furthermore, the first tunable RF filter path **66** is electrically connected between a terminal TU**1** and a terminal TANT**1**. With regard to the second tunable RF filter path **68**, the second tunable RF filter path **68** includes the resonator R(**2,1**), the resonator R(**2,2**), and one or more additional resonators R, such as the resonator R(**2,N**), since the integer N is 3 or greater. All of the weakly coupled resonators R(**2,1**) through R(**2,N**) are weakly coupled to one another. Furthermore, the second tunable RF filter path **68** is electrically connected between a terminal TU**2** and a terminal TANT**2**.

With regard to the third tunable RF filter path **110**, the third tunable RF filter path **110** includes a resonator R(**3,1**), a resonator R(**3,2**), and one or more additional resonators R, such as a resonator R(**3,N**), since the integer N is 3 or greater. All of the weakly coupled resonators R(**3,1**) through R(**3,N**) are weakly coupled to one another. Alternatively, only a proper subset of them may be weakly coupled to one another. Furthermore, the third tunable RF filter path **110** is electrically connected between a terminal TU**3** and a terminal TANT**3**. With regard to the fourth tunable RF filter path **112**, the fourth tunable RF filter path **112** includes the resonator R(**M,1**), the resonator R(**M,2**), and one or more additional resonators R, such as the resonator R(**M,N**), since the integer N is 3 or greater. All of the weakly coupled resonators R(**M,1**) through R(**M,N**) are weakly coupled to one another. Alternatively, only a proper subset of them may be weakly coupled to one another. Furthermore, the fourth tunable RF filter path **112** is electrically connected between a terminal TU**4** and a terminal TANT**4**.

The first tunable RF filter path **66** is configured to receive RF signals and output filtered RF signals. It should be noted that the first RF filter structure **60** may include any number of tunable RF filter paths, such as, for example, the third tunable RF filter path **110**, the fourth tunable RF filter path **112**, the fifth tunable RF filter path **122**, and the sixth tunable RF filter path **124**, described above with respect to FIGS. **11-14**. Each of the resonators R may be a tunable resonator, which allows for a resonant frequency of each of the resonators to be varied to along a frequency range. In alternative embodiments, only a proper subset of the resonators R may be tunable. In still another embodiment, all of the resonators R are not tunable, but rather have a fixed transfer function.

In some embodiments, all of the resonators R in the first RF filter structure **60** shown in FIG. **30** are weakly coupled to one another. Thus, the resonators R may all be operably associated with one another such that energy transfer factors between the resonators R are less than 10%. Alternatively, the energy transfer factor is less than 10% only among a proper subset of the resonators R. In other embodiments, only the resonators R in adjacent tunable RF filter paths **66**, **68**, **110**, **112** are weakly coupled to one another. For example, all the resonators R(**1,1**) through R(**1,N**) may be weakly coupled to all the resonators R(**2,1**) through R(**2,N**). In still other embodiments, only subsets of adjacent resonators R may be weakly coupled to each other. For example, the resonators R(**1,1**), R(**1,2**) may be weakly coupled to the resonators R(**2, 1**), R(**2,2**), while the resonators R(**3,1**), R(**3,2**) may be weakly coupled to the resonators R(**M,1**), R(**M,2**). These and other combinations would be apparent to one of ordinary skill in the art in light of this disclosure.

Sets S(1), S(2), S(3), S(4), S(5), and S(6) of cross-coupled capacitive structures are electrically connected between the resonators R. Each of the sets S(1), S(2), S(3), S(4), S(5), and S(6) is arranged like the set S of cross-coupled capacitive structures described above with respect to FIG. 29. For example, in one particular exemplary embodiment (e.g., when M=4 and N=3), the set S(1) of cross-coupled capacitive structures is electrically connected between the resonators R(1,1), R(1,2) in the first tunable RF filter path 66 and the resonators R(2,1), R(2,2) in the second tunable RF filter path 68. The set S(2) of cross-coupled capacitive structures is electrically connected between the resonators R(1,2), R(1,N) in the first tunable RF filter path 66 and the resonators R(2,2), R(2,N) in the second tunable RF filter path 68. The set S(3) of cross-coupled capacitive structures is electrically connected between the resonators R(2,1), R(2,2) in the second tunable RF filter path 68 and the resonators R(3,1), R(3,2) in the third tunable RF filter path 110. The set S(4) of cross-coupled capacitive structures is electrically connected between the resonators R(2,2), R(2,N) in the second tunable RF filter path 68 and the resonators R(3,2), R(3,N) in the third tunable RF filter path 110. The set S(5) of cross-coupled capacitive structures is electrically connected between the resonators R(3,1), R(3,2) in the third tunable RF filter path 110 and the resonators R(M,1), R(M,2) in the fourth tunable RF filter path 112. Finally, the set S(6) of cross-coupled capacitive structures is electrically connected between the resonators R(3,2), R(3,N) in the third tunable RF filter path 110 and the resonators R(M,2), R(M,N) in the fourth tunable RF filter path 112. Note that some cross-coupled capacitive structures in the sets S(1), S(2), S(3), S(4), S(5), and S(6) of cross-coupled capacitive structures for the resonators R in adjacent columns or in adjacent ones of the tunable RF filter paths 66, 68, 110, 112 overlap. This is because in the matrix of the resonators R, each of the resonators R is adjacent to multiple other ones of the resonators R. In another embodiment, the sets S(1), S(2), S(3), S(4), S(5), and S(6) of cross-coupled capacitive structures may be connected between non-adjacent resonators R. For example, there may be cross-coupled capacitive structures between resonators R that are more than one column or row apart.

FIG. 31 illustrates the embodiment of the first RF filter structure 60 shown in FIG. 30 electrically connected to the first RF antenna 16, the second RF antenna 32, a third RF antenna 246, and a fourth RF antenna 247. More specifically, the first tunable RF filter path 66 is electrically connected to the first RF antenna 16 at the terminal TANT1. The second tunable RF filter path 68 is electrically connected to the second RF antenna 32 at the terminal TANT2. The third tunable RF filter path 110 is electrically connected to the third RF antenna 246 at the terminal TANT3. The fourth tunable RF filter path 112 is electrically connected to the fourth RF antenna 247 at the terminal TANT4. With the sets S(1), S(2), S(3), S(4), S(5), and S(6) of cross-coupled capacitive structures, the first RF filter structure 60 shown in FIG. 31 forms an interconnected two-dimensional matrix of the resonators R. Thus, in addition to the first tunable RF filter path 66, the second tunable RF filter path 68, the third tunable RF filter path 110, and the fourth tunable RF filter path 112, the sets S(1), S(2), S(3), S(4), S(5), and S(6) of cross-coupled capacitive structures provide a multitude of additional tunable RF filter paths between the terminals TU1, TU2, TU3, TU4 and the terminals TANT1, TANT2, TANT3, TANT4. It should be noted that in alternative embodiments, the terminals TANT1, TANT2, TANT3, TANT4 may not be connected to antennas. Some antennas may be omitted depending on the functionality being realized.

By tuning the sets S(1), S(2), S(3), S(4), S(5), and S(6), the first RF filter structure 60 shown in FIG. 31 can be tuned so that any combination of the resonators R is selectable for the propagation of RF signals. More specifically, the first RF filter structure 60 shown in FIG. 31 is tunable to route RF receive signals from any combination of the terminals TANT1, TANT2, TANT3, TANT4 to any combination of the terminals TU1, TU2, TU3, TU4. Additionally, the first RF filter structure 60 shown in FIG. 31 is tunable to route RF transmission signals from any combination of the terminals TU1, TU2, TU3, TU4 to the terminals TANT1, TANT2, TANT3, TANT4. Accordingly, the first RF filter structure 60 can be configured to implement various MIMO, SIMO, MISO, and SISO operations.

FIG. 32 illustrates the first RF filter structure 60 shown in FIGS. 30 and 31 with examples of additional tunable RF filter paths 248, 250 highlighted. It should be noted, however, that there are a vast number of additional combinations of the resonators R that may be selected to provide tunable RF filter paths (e.g., the first tunable RF filter path 66, the second tunable RF filter path 68, the third tunable RF filter path 110, the fourth tunable RF filter path 112, the additional tunable RF filter path 248, and the additional tunable RF filter path 250) between the terminals TU1, TU2, TU3, TU4 and the terminals TANT1, TANT2, TANT3, TANT4. An explicit description of all of the various combinations of the resonators R that may be implemented with the first RF filter structure 60 shown in FIGS. 30-32 is simply impractical given the high number of possible combinations. Along with the previous descriptions, the additional tunable RF filter paths 248, 250 are highlighted in FIG. 32 simply to give examples of the basic concepts. However, the combinations provided for the additional tunable RF filter paths 248, 250 are in no way limiting, as any combination of the resonators R may be selected to route RF signals between the terminals TU1, TU2, TU3, TU4 and the terminals TANT1, TANT2, TANT3, TANT4. Any number of functions, such as signal combining, splitting, multiplexing, and demultiplexing, with various filtering profiles for each, may be realized.

With regard to the additional tunable RF filter paths 248, 250 highlighted in FIG. 32, the additional tunable RF filter paths 248, 250 may be used during MIMO, SIMO, MISO, and SISO operations. More specifically, the additional tunable RF filter path 248 connects the terminal TANT1 to the terminal TU2. The additional tunable RF filter path 250 connects the terminal TANT3 to the terminal TU2. As such, the first RF filter structure 60 may be tuned so that the additional tunable RF filter path 248 and the additional tunable RF filter path 250 are selected in a MISO operation from the terminal TANT1 and the terminal TANT3 to the terminal TU2. The additional tunable RF filter paths 248, 250 may also be used in SIMO operations. For example, the first RF filter structure 60 may be tuned so that the first tunable RF filter path 66 and the additional tunable RF filter path 248 are selected in a SIMO operation from the terminal TU2 to the terminal TANT1. The additional tunable RF filter paths 248, 250 can also be used in SISO operations from the terminal TANT1 to the terminal TU2 or from the terminal TANT3 to the terminal TU2. Finally, the additional tunable RF filter paths 248, 250 may also be used in SIMO operations. For instance, the first RF filter structure 60 may be tuned so that the first tunable RF filter path 66 and the additional tunable RF filter path 250 are selected in a SIMO operation from the terminal TANT1 to the terminal TU1 and from the terminal TANT3 to the terminal TU2.

In some applications involving the first RF filter structure 60 in FIGS. 30-32, MISO and SIMO operations can be used

in conjunction with wideband antenna cables or fiber for transmitting RF signals in multiple RF communication frequency bands. Specific communication frequency bands can be processed by certain dedicated RF filtering paths in the first RF filter structure **60**. For example, different RF signals may be injected from a wideband antenna and then propagated along different dedicated tunable RF filter paths in the first RF filter structure **60** to the terminals TU1, TU2, TU3, TU4. These dedicated tunable RF filter paths can be configured to have a transfer function that is specifically designed to handle these RF signals. Furthermore, the first RF filter structure **60** shown in FIGS. **30-32** is configured to tune a transfer function of any of the specific tunable RF filter paths (e.g., the first tunable RF filter path **66**, the second tunable RF filter path **68**, the third tunable RF filter path **110**, the fourth tunable RF filter path **112**, the additional tunable RF filter path **248**, and the additional tunable RF filter path **250**) in the first RF filter structure **60** by tuning resonators R that are not in the specific tunable RF filter path being used to route RF signals. This can help reduce out-of-band noise and reduce insertion losses. It can also improve isolation and out-of-band attenuation.

FIG. **33** illustrates yet another embodiment of the first RF filter structure **60**. The first RF filter structure **60** includes the resonators R and is arranged as a two-dimensional matrix of the resonators R, where N is equal to four (4) and M is equal to three (3). In this embodiment, the first RF filter structure **60** includes an embodiment of the first tunable RF filter path **66**, an embodiment of the second tunable RF filter path **68**, and an embodiment of the third tunable RF filter path **110**. It should be noted that in alternative embodiments, the number of resonators R in each row and column may be the same or different.

In the embodiment of the first RF filter structure **60** shown in FIG. **33**, the first tunable RF filter path **66** includes the resonator R(**1,1**), the resonator R(**1,2**), the resonator R(**1,3**), and the resonator R(**1,4**). Furthermore, the first tunable RF filter path **66** is electrically connected between the terminal TU1 and the terminal TANT1. With regard to the second tunable RF filter path **68**, the second tunable RF filter path **68** includes the resonator R(**2,1**), the resonator R(**2,2**), a resonator R(**2,3**), and a resonator R(**2,4**). Furthermore, the second tunable RF filter path **68** is electrically connected between the terminal TU2 and the terminal TANT2. With regard to the third tunable RF filter path **110**, the third tunable RF filter path **110** includes the resonator R(**3,1**), the resonator R(**3,2**), a resonator R(**3,3**), and a resonator R(**3,4**). Furthermore, the third tunable RF filter path **110** is electrically connected between the terminal TU3 and the terminal TANT3.

In this embodiment, the resonators R in a subset **252** of the resonators R(**1,1**), R(**1,2**) in the first tunable RF filter path **66** are weakly coupled to one another. A cross-coupling capacitive structure CS1 is electrically connected between the resonators R(**1,1**), R(**1,2**). The cross-coupling capacitive structure CS1 is a variable cross-coupling capacitive structure configured to vary a variable electric coupling coefficient between the resonators R(**1,1**), R(**1,2**). A subset **254** of the resonators R(**1,3**), and R(**1,4**) in the second tunable RF filter path **68** is also weakly coupled to each other. A cross-coupling capacitive structure CS2 is electrically connected between the resonators R(**1,3**), R(**1,4**). The cross-coupling capacitive structure CS2 is a variable cross-coupling capacitive structure configured to vary a variable electric coupling coefficient between the resonators R(**1,3**), R(**1,4**).

As shown in FIG. **33**, a unidirectional coupling stage **256** is electrically connected within the first tunable RF filter path **66**. The unidirectional coupling stage **256** defines an amplifier gain and is configured to provide amplification within the first tunable RF filter path **66** in accordance with the amplifier

gain. In some embodiments, the amplifier gain of the unidirectional coupling stage **256** is a variable amplifier gain. In this embodiment, the unidirectional coupling stage **256** is electrically connected between the resonator R(**1,2**) and the resonator R(**1,3**). The variable amplifier gain can thus control a variable electric coupling coefficient between the resonator R(**1,2**) in the subset **252** and the resonator R(**1,3**) in the subset **254**. Since the unidirectional coupling stage **256** is an active semiconductor component, the unidirectional coupling stage **256** is unidirectional and thus only allows signal propagations from an input terminal IA of the unidirectional coupling stage **256** to an output terminal OA of the unidirectional coupling stage **256**. Thus, the resonator R(**1,2**) in the subset **252** is unidirectionally mutual electrically coupled to the resonator R(**1,3**) in the subset **254**.

Note that the resonators R(**1,3**), R(**1,4**) in the subset **254** are not electrically connected to the second tunable RF filter path **68** and the third tunable RF filter path **110**. As such, the unidirectional coupling stage **256** thus results in a portion of the first tunable RF filter path **66** with the subset **254** of the resonators R(**1,3**), R(**1,4**) to be unidirectional. Consequently, signal flow can be to the terminal TANT1 but not from the terminal TANT1. Since the unidirectional coupling stage **256** is unidirectional, the variable amplifier gain (and thus the variable electric coupling coefficient between the resonator R(**1,2**) and the resonator R(**1,3**)) may be controlled using feed-forward control techniques and/or feedback control techniques.

Next, the resonators R in a subset **258** of the resonators R(**2,1**), R(**2,2**), R(**3,1**), and R(**3,2**) in the second tunable RF filter path **68** and in the third tunable RF filter path **110** are weakly coupled to one another. An unidirectional coupling stage **260** is electrically connected between the first tunable RF filter path **66** and the second tunable RF filter path **68**. More specifically, the unidirectional coupling stage **260** is electrically connected between the resonator R(**1,1**) and the resonator R(**2,1**). The unidirectional coupling stage **260** defines an amplifier gain and is configured to provide amplification in accordance with the amplifier gain. In some embodiments, the amplifier gain of the unidirectional coupling stage **260** is a variable amplifier gain. The variable amplifier gain thus can control a variable electric coupling coefficient between the resonator R(**1,1**) in the subset **252** and the resonator R(**2,1**) in the subset **258**. A cross-coupling capacitive structure CS3 is electrically connected between the resonator R(**1,2**) and the resonator R(**2,2**). The cross-coupling capacitive structure CS3 is a variable cross-coupling capacitive structure configured to vary a variable electric coupling coefficient between the resonators R(**1,2**), R(**2,2**).

To interconnect the resonators R(**2,1**), R(**2,2**), R(**3,1**), and R(**3,2**), a set S(A) of cross-coupling capacitive structures is electrically connected between the resonators R(**2,1**), R(**2,2**), R(**3,1**), and R(**3,2**) in the subset **258**. The set S(A) of cross-coupling capacitive structures is arranged like the set S of cross-coupling capacitive structures described above with respect to FIG. **29**. Additionally, the resonators R in a subset **262** of the resonators R(**2,3**), R(**2,4**), R(**3,3**), and R(**3,4**) in the second tunable RF filter path **68** and in the third tunable RF filter path **110** are weakly coupled to one another. A set S(B) of cross-coupling capacitive structures is electrically connected between the resonators R(**2,3**), R(**2,4**), R(**3,3**), and R(**3,4**) in the subset **262**. The set S(B) of cross-coupling capacitive structures is arranged like the set S of cross-coupling capacitive structures described above with respect to FIG. **29**.

To interconnect the subset **258** and the subset **262**, the first RF filter structure **60** shown in FIG. **33** includes a cross-

coupling capacitive structure CS4 and a unidirectional coupling stage 264. The cross-coupling capacitive structure CS4 is electrically connected between the resonators R(2,2), R(2,3). The cross-coupling capacitive structure CS4 is a variable cross-coupling capacitive structure configured to vary a variable electric coupling coefficient between the resonators R(2,2), R(2,3). The unidirectional coupling stage 264 is electrically connected within the third tunable RF filter path 110. In this embodiment, the unidirectional coupling stage 264 is electrically connected between the resonator R(3,3) and the resonator R(3,2). The unidirectional coupling stage 264 defines an amplifier gain and is configured to provide amplification within the third tunable RF filter path 110 in accordance with the amplifier gain. In some embodiments, the amplifier gain of the unidirectional coupling stage 264 is a variable amplifier gain. The variable amplifier gain can thus control a variable electric coupling coefficient between the resonator R(3,3) in the subset 262 and the resonator R(3,2) in the subset 258. Since the unidirectional coupling stage 264 is an active semiconductor component, the unidirectional coupling stage 264 is unidirectional and thus only allows signal propagations from an input terminal IB of the unidirectional coupling stage 264 to an output terminal OB of the unidirectional coupling stage 264. Thus, the resonator R(3,3) in the subset 262 is unidirectionally mutual electrically coupled to the resonator R(3,2) in the subset 258. Consequently, the third tunable RF filter path 110 shown in FIG. 33 is unidirectional if the signal flow is between the terminal TANT3 and the terminal TU3 though the third tunable RF filter path 110. As such signal flow between the terminal TANT3 and the terminal TU3 is provided only through the third tunable RF filter path 110, signal flow can only be from the terminal TANT3 to the terminal TU3, and not vice versa. In other cases, an additional tunable RF signal path (e.g., the additional RF terminal tunable RF signal path that includes the resonators R(3,1), R(2,2), R(2,3) and R(3,4)) can be tuned to provide bidirectional signal flow between the terminal TU3 and the terminal TANT3 through the cross-coupling capacitive structure CS4. The unidirectional coupling stages 256, 260, 264 may be active devices, such as amplifiers, diodes, transistors, networks of transistors, buffer stages, attenuation stages, and the like. The unidirectional coupling stages 256, 260, 264 can have gains higher than one (1), lower than one (1), or equal to one (1). Additionally, the unidirectional coupling stages 256, 260, 264 may be passive devices. The unidirectional coupling stages 256, 260, 264 may not be entirely or ideally unilateral, but may have some finite reverse coupling. In this case, the unidirectional coupling stages 256, 260, 264 may be predominately unilateral. One example in which the unidirectional coupling stages 256, 260, 264 may be used for multi-resonator applications and may improve isolation between certain parts, such as transmission ports and receive ports of a duplexer.

FIG. 34 illustrates yet another embodiment of the first RF filter structure 60. The first RF filter structure 60 shown in FIG. 34 is integrated into an IC package 266. The first RF filter structure 60 shown in FIG. 34 includes the resonators R and is arranged as a two-dimensional matrix of the resonators R, where N is equal to three (3) and M is equal to two (2). It should be noted that in alternative embodiments the number of resonators R in each row and column may be the same or different.

In this embodiment, the first RF filter structure 60 includes an embodiment of the first tunable RF filter path 66 and an embodiment of the second tunable RF filter path 68. The first tunable RF filter path 66 includes the resonator R(1,1), the resonator R(1,2), and the resonator R(1,3). The second tunable RF filter path 68 includes the resonator R(2,1), the resonator R(2,2), and the resonator R(2,3). A set S(X) of cross-coupling capacitive structures is electrically connected between the resonators R(1,1), R(1,2), R(2,1), and R(2,2). The set S(X) of cross-coupling capacitive structures is arranged like the set S of cross-coupling capacitive structures described above with respect to FIG. 29. A set S(Y) of cross-coupling capacitive structures is electrically connected between the resonators R(1,2), R(1,3), R(2,2), and R(2,3). The set S(Y) of cross-coupling capacitive structures is also arranged like the set S of cross-coupling capacitive structures described above with respect to FIG. 29.

As shown in FIG. 34, the IC package 266 houses a package substrate 268, a semiconductor die 270, and a semiconductor die 272. The semiconductor die 270 and the semiconductor die 272 are mounted on the package substrate 268. In this embodiment, the resonators R of the first RF filter structure 60 are formed by the package substrate 268. The set S(X) of cross-coupling capacitive structures is formed by the semiconductor die 270. On the other hand, the set S(Y) of cross-coupling capacitive structures is formed by the semiconductor die 272. Thus, the set S(X) of cross-coupling capacitive structures and the set S(Y) of cross-coupling capacitive structures are formed on multiple and separate semiconductor dies 270, 272. Using the multiple and separate semiconductor dies 270, 272 may be helpful in order to increase isolation. The multiple and separate semiconductor dies 270, 272 may have less area than the semiconductor die 268 shown in FIG. 34. As such, the embodiment shown in FIG. 35 may consume less die area.

FIG. 35 illustrates another embodiment of an IC package 266' that houses the same embodiment of the first RF filter structure 60 described above with regard to FIG. 34. The IC package 266' is the same as the IC package 266 shown in FIG. 34, except that the IC package 266' only has a single semiconductor die 274. In this embodiment, both the set S(X) of cross-coupling capacitive structures and the set S(Y) of cross-coupling capacitive structures are formed by the semiconductor die 272. Thus, the IC package 266' allows for a more compact arrangement than the IC package 266.

FIG. 36 illustrates yet another embodiment of the first RF filter structure 60. In this embodiment, the first RF filter structure 60 is arranged as a three-dimensional matrix of resonators R1, R2, R3. More specifically, a two-dimensional matrix of the resonators R1 is provided on a plane k, a two-dimensional array of the resonators R2 is provided on a plane m, and a two-dimensional array of the resonators R3 is provided on a plane n. Cross-coupling capacitive structures CC are electrically connected between the resonators R1, R2, R3 that are adjacent to one another in the same plane k, m, n and in the different planes k, m, n. The three-dimensional matrix of resonators R1, R2, R3 thus allows for more resonators to be cross-coupled to one another. This allows for the first RF filter structure 60 to provide greater numbers of tunable RF filter paths and allows for the first RF filter structure 60 to be tuned more accurately.

In general, having more tunable RF filter paths allows for the synthesis of a more complex transfer function with multiple notches for better blocker rejection. The number of resonators R1, R2, R3 in each of the planes k, n, m may be different or the same. The three-dimensional matrix of resonators can be used in MIMO, SIMO, MISO, and SISO applications.

Those skilled in the art will recognize improvements and modifications to the preferred embodiments of the present

disclosure. All such improvements and modifications are considered within the scope of the concepts disclosed herein and the claims that follow.

What is claimed is:

1. A radio frequency (RF) filter structure comprising:
a first resonator comprising:
a first inductor; and
a first capacitive structure electrically connected to the first inductor;
a second resonator operably associated with the first resonator such that an energy transfer factor between the first resonator and the second resonator is less than 10%, wherein the second resonator comprises:
a second inductor having a maximum lateral width and wherein a displacement between the first inductor and the second inductor is less than or equal to half the maximum lateral width;
a second capacitive structure electrically connected to the second inductor;
a first cross-coupling capacitive structure electrically connected between the first resonator and the second resonator; and
a second cross-coupling capacitive structure electrically connected between the first resonator and the second resonator, wherein:
the first cross-coupling capacitive structure is electrically connected between the first resonator and the second resonator so as to provide a positive coupling coefficient between the first resonator and the second resonator; and
the second cross-coupling capacitive structure is electrically connected between the first resonator and the second resonator so as to provide a negative coupling coefficient between the first resonator and the second resonator.

2. The RF filter structure of claim 1 wherein the second inductor is smaller than the first inductor.

3. The RF filter structure of claim 1 wherein the first inductor and the second inductor are of a same size.

4. The RF filter structure of claim 1 wherein the first inductor is a first folded inductor configured to generate a first confined magnetic field.

5. The RF filter structure of claim 4 wherein the second inductor is a second folded inductor configured to generate a second confined magnetic field.

6. The RF filter structure of claim 1 wherein the first inductor and the second inductor are arranged such that a mutual magnetic coupling between the first inductor and the second inductor cancel.

7. The RF filter structure of claim 1 wherein the first inductor and the second inductor are arranged so as to provide a negative mutual magnetic coupling coefficient between the first inductor and the second inductor.

8. The RF filter structure of claim 1 wherein the first capacitive structure is a first variable capacitive structure.

9. The RF filter structure of claim 8 wherein the second capacitive structure is a second variable capacitive structure.

10. The RF filter structure of claim 1 comprising a first filter path, wherein the first filter path includes the first resonator, the second resonator, and the first cross-coupling capacitive structure.

11. The RF filter structure of claim 10 wherein the first filter path further comprises:
a third resonator comprising:
a third inductor; and
a third capacitive structure electrically connected to the third inductor; and

the second cross-coupling capacitive structure electrically connected between the first resonator and the third resonator.

12. The RF filter structure of claim 11 wherein:
the second cross-coupling capacitive structure is electrically connected between the first resonator and the third resonator so as to provide the negative coupling coefficient between the first resonator and the third resonator.

13. The RF filter structure of claim 10 further comprising a second filter path, wherein the second filter path comprises:
a third resonator comprising:
a third inductor; and
a third capacitive structure electrically connected to the first inductor;
a fourth resonator operably associated with the third inductor such that the energy transfer factor between the first resonator and the second resonator is less than 10%, wherein the fourth resonator comprises:
a fourth inductor having a maximum lateral width and wherein a displacement between the third inductor and the fourth inductor is less than or equal to half the maximum lateral width; and
a fourth capacitive structure electrically connected to the fourth inductor; and
the second cross-coupling capacitive structure electrically connected between the third resonator and the fourth resonator.

14. The first RF filter structure of claim 1 wherein:
the first cross-coupling capacitive structure is a first variable cross-coupling capacitive structure configured to vary the positive coupling coefficient provided between the first resonator and the second resonator; and
the second cross-coupling capacitive structure is a second variable cross-coupling capacitive structure configured to vary the negative coupling coefficient provided between the first resonator and the second resonator.

15. The RF filter structure of claim 1 wherein:
the first resonator is a first differential resonator; and
the second resonator is a second differential resonator.

16. The RF filter structure of claim 1 further comprising:
a third cross-coupling capacitive structure electrically connected between the first resonator and the second resonator so as to provide an other positive coupling coefficient between the first resonator and the second resonator; and
a fourth cross-coupling capacitive structure electrically connected between the first resonator and the second resonator so as to provide an other negative coupling coefficient between the first resonator and the second resonator.

17. The RF filter structure of claim 16 wherein:
the first inductor has a first end and a second end; and
the second inductor has a third end and a fourth end, wherein the first inductor is magnetically coupled to the second inductor such that a radio frequency (RF) signal received at the first end of the first inductor with a first voltage polarity results in a filtered RF signal being transmitted out the third end of the second inductor with the first voltage polarity.

18. The RF filter structure of claim 17 wherein:
the first cross-coupling capacitive structure is electrically connected between the first end and the third end;
the second cross-coupling capacitive structure is electrically connected between the first end and the fourth end;
the third cross-coupling capacitive structure is electrically connected between the second end and the fourth end; and

the fourth cross-coupling capacitive structure is electrically connected between the second end and the third end.

19. The RF filter structure of claim 18 wherein:

the first cross-coupling capacitive structure is a first variable cross-coupling capacitive structure configured to vary the positive coupling coefficient provided between the first resonator and the second resonator;

the second cross-coupling capacitive structure is a second variable cross-coupling capacitive structure configured to vary the negative coupling coefficient provided between the first resonator and the second resonator;

the third cross-coupling capacitive structure is a third variable cross-coupling capacitive structure configured to vary the other positive coupling coefficient provided between the first resonator and the second resonator; and

the fourth cross-coupling capacitive structure is a fourth variable cross-coupling capacitive structure configured to vary the other negative coupling coefficient provided between the first resonator and the second resonator.

20. The RF filter structure of claim 1 further comprising:

a plurality of resonators that includes the first resonator and the second resonator; and

a unidirectional coupling stage;

wherein the plurality of resonators has cross-coupling coefficients and at least one of the cross-coupling coefficients is provided by the unidirectional coupling stage.

21. The RF filter structure of claim 1 wherein:

the first resonator is a single-ended resonator; and

the second resonator is a differential resonator.

22. A radio frequency (RF) filter structure comprising:

a first resonator comprising:

   a first inductor; and

   a first capacitive structure electrically connected to the first inductor;

a second resonator operably associated with the first resonator such that an energy transfer factor between the first resonator and the second resonator is less than 10%, wherein the second resonator comprises:

   a second inductor having a maximum lateral width and wherein a displacement between the first inductor and the second inductor is less than or equal to half the maximum lateral width; and

   a second capacitive structure electrically connected to the second inductor;

a first cross-coupling capacitive structure electrically connected between the first resonator and the second resonator; and

a second cross-coupling capacitive structure, wherein the first cross-coupling capacitive structure and the second cross-coupling capacitive structure are arranged to form a first capacitive voltage divider.

23. The RF filter structure of claim 22 further comprising a third cross-coupling capacitive structure and a fourth cross-coupling capacitive structure, wherein:

the third cross-coupling capacitive structure and the fourth cross-coupling capacitive structure are arranged so as to form a second capacitive voltage divider;

the first capacitive voltage divider is electrically connected to the first resonator; and

the second capacitive voltage divider is electrically connected to the second resonator.

24. The RF filter structure of claim 23 wherein each of the first cross-coupling capacitive structure, the second cross-coupling capacitive structure, the third cross-coupling capacitive structure, and the fourth cross-coupling capacitive structure is a variable capacitive structure.

25. The RF filter structure of claim 23 further comprising a fifth cross-coupling capacitive structure and a sixth cross-coupling capacitive structure, wherein the fifth cross-coupling capacitive structure and the sixth cross-coupling capacitive structure are arranged to form a third capacitive voltage divider.

26. The RF filter structure of claim 25 wherein further comprising a seventh cross-coupling capacitive structure and an eighth cross-coupling capacitive structure, wherein:

the seventh cross-coupling capacitive structure and the eighth cross-coupling capacitive structure are arranged so as to form a fourth capacitive voltage divider;

the third capacitive voltage divider is electrically connected to the first resonator; and

the fourth capacitive voltage divider is electrically connected to the second resonator.

27. The RF filter structure of claim 26 wherein each of the first cross-coupling capacitive structure, the second cross-coupling capacitive structure, the third cross-coupling capacitive structure, the fourth cross-coupling capacitive structure, the fifth cross-coupling capacitive structure, the sixth cross-coupling capacitive structure, the seventh cross-coupling capacitive structure, and the eighth cross-coupling capacitive structure is a variable capacitive structure.

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